U.S. DEPARTMENT OF COMMERCE
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PB-271 894

Air Quality in the Denver Metropolitan Region 1974-2000

Systems Applications, Inc, San Rafael, Calif

Prepared for

Environmental Protection Agency, Denver, Colo Region VIII

May 77

EPA-908/1-77-002

PB 271 894

AIR QUALITY IN DENVER METROPOLITAN REGION 1974-2000

ENVIRONMENTAL PROTECTION AGENCY

REGION VIII

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-908/1-77-002

2.

3. RECIPIENT'S ACCESSION NO. PB-271 894

4. TITLE AND SUBTITLE
Air Quality in the Denver Metropolitan Region 1974-2000

5. REPORT DATE May 1977

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NO. EF77-222

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Systems Applications, Incorporated
950 Northgate Drive
San Rafael, California 94903

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO. 68-01-4341

12. SPONSORING AGENCY NAME AND ADDRESS
Environmental Protection Agency, Region VIII
1860 Lincoln Street
Denver, Colorado 80203

13. TYPE OF REPORT AND PERIOD COVERED Final Report: 10/76 - 4/77

14. SPONSORING AGENCY CODE 908/00

15. SUPPLEMENTARY NOTES

16. ABSTRACT

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Projections of photochemical oxidant concentrations, exposures, and dosages were obtained with the Denver Air Quality Model. DAQM, developed during this program, is based on previous Systems Applications, Inc. (SAI) photochemical models. A validation study showed that DAQM, without calibration, does not consistently under- or over-predict peak oxidant concentrations. At least 80 percent of the predictions were within a factor of two of the observations. Air quality projections were found to be negligibly affected by major changes in projected land use and less than proportionately affected by large changes in atmospheric dispersion.

Measures proposed to mitigate adverse air quality were examined. The only measure identified as having significant mitigation potential was the control of vehicle emission factors. The effects of that measure were found to be large, complex, and not predictable by simple methods.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT
Release to Public

19. SECURITY CLASS *(This Report)* Unclassified

20. SECURITY CLASS *(This page)* Unclassified

21. NO. OF PAGES 468

22. PRICE PCA20-A01

EPA Form 2220-1 (9-73)

*U.S. Government Printing Office: 1977-780-080/267 Region 8

EPA-908/1-77-002
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FOREWORD

Estimates of Denver's present and future air quality have been made independently of this study by the staffs of the Colorado Division of Highways and the Colorado Department of Health. These other studies, including the recently released Air Quality Maintenance Analysis by the Health Department's Air Pollution Control Division, made use of the Air Pollution Simulation Program developed by Systems Applications, Incorporated (SAI), which is an antecedent of the Denver Air Quality Model used in the present study.

We have not reviewed the AQMA and we do not know to what extent its conclusions are consistent with those of this report. The major difference between DAQM and APSP is the more advanced Carbon-Bond photochemical oxidant mechanism used in the DAQM. The Carbon-Bond mechanism has only become available with this study. We feel that DAQM is the preferred simulation model. Other differences between the conclusions of the various reports may arise from the cases studied and input conditions assumed. Differences in interpretation of results might naturally be expected from different investigators. We suggest that the interested reader examine all these reports for complementary information.

ABSTRACT

This report describes an air quality analysis for the Denver metropolitan region for the years 1976, 1985, and 2000. The analysis was carried out to provide background information as to the environmental impact of the urban growth that might be associated with the availability of new wastewater treatment facilities. Generally improving air quality is forecast, although exceedences of some air quality standards are projected. These results are based on physico-chemical computer simulations using pollutant emissions forecasts.

Projections of photochemical oxidant concentrations, exposures, and dosages were obtained with the Denver Air Quality Model. DAQM, developed during this program, is based on previous Systems Applications, Inc. (SAI) photochemical models. A validation study showed that DAQM, without calibration, does not consistently under- or over-predict peak oxidant concentrations. At least 80 percent of the predictions were within a factor of two of the observations. Air quality projections were found to be negligibly affected by major changes in projected land use and less than proportionately affected by large changes in atmospheric dispersion.

Measures proposed to mitigate adverse air quality were examined. The only measure identified as having significant mitigation potential was the control of vehicle emission factors. The effects of that measure were found to be large, complex, and not predictable by simple methods.

CONTENTS

FOREWARD iii

ABSTRACT v

ACKNOWLEDGMENTS xi

I OVERVIEW 1

- A. Summary of Results 1
- B. Purpose of Project 3
- C. Structure of Project and Report 4
- D. Air Quality Modeling 7
  - 1. General Considerations 7
  - 2. Characteristics of the Denver Region 10
- E. Model Validation Studies 16
- F. Base Case Studies 25
  - 1. Ozone 25
  - 2. Carbon Monoxide 28
  - 3. Nitrogen Dioxide 31
  - 4. Particulates 33
- G. Sensitivity Studies 33
- H. Mitigation Studies 35
- I. Recommendations 39

II DENVER AIR QUALITY MODEL VALIDATION STUDY 41

- A. Simulation Cases 42
- B. Observations and Computed Results 43
- C. Validation Results 45
  - 1. Comparisons of Ozone Predictions and Observations . 45
  - 2. Analysis of Ozone Comparisons 55
  - 3. Carbon Monoxide Comparisons 67
  - 4. Nitrogen Oxide Comparisons 74
- D. Comparison of the Denver Model with Other Models . . . 78
- E. Conclusions 83

III BASE CASE STUDIES 85

A. Base Case Ozone Concentrations Predicted by the Denver Model 86

1. Station Comparisons 86
2. Area Comparisons 89

B. Base Case Carbon Monoxide Concentrations Predicted by the Denver Model 92

C. Base Case NO_2 and Particulate Concentrations Predicted by the CDM 94

IV SENSITIVITY ANALYSIS 127

A. Sensitivity of Predictions of the Denver Model to Meteorological Variables 127

B. Sensitivity of Predictions of the Denver Model and CDM to the Spatial Distribution of Emissions. 133

1. Denver Model 141
2. Climatological Dispersion Model 142

C. Conclusions 158

V MITIGATION CONSIDERATIONS 159

A. Growth Projections 159

B. Vehicle Emission Factors 160

C. Additional Mitigation Studies 162

1. Mass Transit 163
2. Hydrocarbon Vapor Recovery 163

D. Implications for Mitigation Strategies of Additional Simulations 167

1. Effects of 30 Percent Reduction in All Emissions . 167
2. Effects of Relaxation of the Federal NO_x Emissions Standard 171

VI EXPOSURE AND DOSAGE STUDIES 179

A. Dosage Calculations 179

B. Exposure Calculations 180

C. Inputs Necessary for Exposure and Dosage Calculations . 181

1. Ozone Concentrations 181
2. Population Distributions 182
3. Adjustments to Population Distributions 190

D. Exposure and Dosage Estimates 191

E. Summary and Conclusions 213

REFERENCES FOR MAIN TEXT 214

APPENDICES

A DESCRIPTION OF THE MODELS 217

1. The Modeling Region and Boundary Conditions 219
2. The Emissions Inventory 220
3. The Meteorological File and Diffusivity Algorithm . 221
4. Treatment of Chemical Reactions 222
5. Parameterization of the Denver Model 250
6. The Climatological Dispersion Model (CDM) 264

REFERENCES FOR APPENDIX A 267

B EMISSIONS ANALYSIS 271

1. Overview of Present Emissions in the Denver Region 273
2. Emissions Standards and Regulations Applicable to Highway and Other Traffic 274
3. Methodologies Used for Estimation and Projection of Emissions 275
4. Analysis of Emissions Input to the CDM 297
5. Analysis of Emissions Input to the Denver Model . . 310

C DENVER REGIONAL PLANNING OVERVIEW 341

1. Introduction 343
2. Organizational Perspectives 346
3. Overview of Planning Issues 376
4. Summary and Recommendations 445

ANNEX C-1 A SIMPLIFIED POPULATION FORECASTING METHOD . . . 452

ANNEX C-2 NATIONAL AMBIENT AIR QUALITY STANDARDS 457

REFERENCES FOR APPENDIX C 459

ACKNOWLEDGMENTS

Completion of this program would not have been possible within the resources available without the extensive prior efforts of Colorado Division of Highways, the Air Pollution Control Division of the Colorado Public Health Department, the Denver Regional Council of Governments, the Regional Transportation District, and EPA Region VIII offices.

In addition to creating valuable data files and carrying out valuable modeling and other analyses, the agencies noted above were most cooperative in transmitting their work and data to us. This was done graciously in spite of what often was substantial inconvenience to their own work schedules.

Clearly the credit and thanks are due real people, not just agencies, but, to avoid injustice from any slips on our part, we register this heartfelt thanks to "everybody."

I OVERVIEW

A. SUMMARY OF RESULTS

Systems Applications, Inc. (SAI) carried out an air quality analysis of the Denver metropolitan region for present and future conditions using an improved version of the SAI's Air Pollution Simulation Program (APSP) and the EPA's Climatological Dispersion Model (CDM). The new version of APSP incorporates current atmospheric photochemistry concepts through use of SAI's Carbon-Bond chemistry module. The new version will be described herein as the Denver Air Quality Model (DAQM), or simply the Denver Model.

The results of SAI's air quality analysis for Denver indicate that

> The accuracy of the ozone concentrations predicted by the DAQM is on the order of the accuracy of the ozone monitoring instruments.

> Validity measures for one-hour-average ozone concentrations predicted by DAQM equal or exceed the same measures reported by the EPA for EPA-recommended annual-average Gaussian models applied to SO_2.

> The ozone monitoring system in Denver, which is composed of 9 stations, is unlikely to detect actually occurring peak ozone concentrations.

> Peak ozone concentrations in the Denver metropolitan region will decrease significantly in the next three decades in spite of projected growth if Federal vehicle emission standards are met.

> Failure to meet Federal vehicle emission standards would impede achievement of air quality standards. An effective vehicle inspection and maintenance program would aid in achievement of the standards.

> Reduction of hydrocarbon (HC) emissions is more important than reduction of emissions of oxides of nitrogen (NO_x) for lowering ozone concentrations in the modeled region.

> Gasoline station vapor controls could reduce HC emissions by about 5 percent. This would lead to reductions of less than 1 pphm in peak ozone concentrations.

> If HC emissions are preferentially reduced, HC emissions in downwind areas may still react with the excess NO_2 left in Denver's urban plume.

> If total regional emissions are unchanged, reduction of HC and NO_x emissions by 25 percent in any given suburb or cluster of suburbs would have negligible effect on local or regional ozone concentrations.

> Reduction of HC and NO_x emissions by a uniform percentage over the entire Denver region would reduce peak ozone concentrations by about one-half of that percentage.

> A change in the regional average ratio of NO_x to HC emissions would have a significant effect on ozone concentrations. Relaxation of the 1985 Federal vehicle emission factor from 0.4 grams of NO_x per mile to about 1 gram per mile would eliminate violations of the Federal oxidant standard.

> Carbon monoxide concentrations averaged over two-mile-square grid cells do not now exceed standards. Standards are violated at smaller "hot spots." CO concentrations should be much lower in the future and the number of hot spot violations should decrease.

> The Denver region is probably now in compliance with NO_2 standards. Future NO_2 concentrations cannot be confidently predicted. Conflicting results were obtained with two types of analysis. Our best estimate is that NO_2 concentrations will not rise markedly over the next three decades if Federal vehicle emissions standards are met.

> Violations of particulate standards now occur. Violations will probably become more severe over the next three decades.

B. PURPOSE OF PROJECT

This analysis of present and future air quality in the Denver region was undertaken in response to the Environmental Protection Agency (EPA) Request for Proposal (RFP) WA-76-B576. That document states that

> . . . twelve wastewater treatment and collection facilit[ies] . . . considered together . . . raise significant regional issues which must be addressed such as air quality, [etc.] . . . A regional environmental overview study has been suggested as one possible way to evaluate these issues . . . The analysis of regional issues has been difficult using a project-by project approach. . . It now appears time to prepare a regional environmental impact statement . . .
>
> A portion of this study involves the testing of future strategies against attainment and maintenance of air quality standards.

The RFP also states that the "EPA does not consider the preparation of this EIS [Environmental Impact Statement] to be the development of an air quality plan" and "EPA does not intend to develop a new air quality land use plan . . . EPA must evaluate the environmental impacts of its major actions and must devise mitigation measures for adverse impacts which are identified."

SAI contracted with EPA Region VIII offices in Denver to analyze the effects on Denver's air quality of the urban growth and development that would be supported by the availability of the proposed wastewater treatment facilities. EPA Region VIII is preparing an overview EIS for the entire multi-unit project, and the SAI air quality analysis provides input to the EIS.

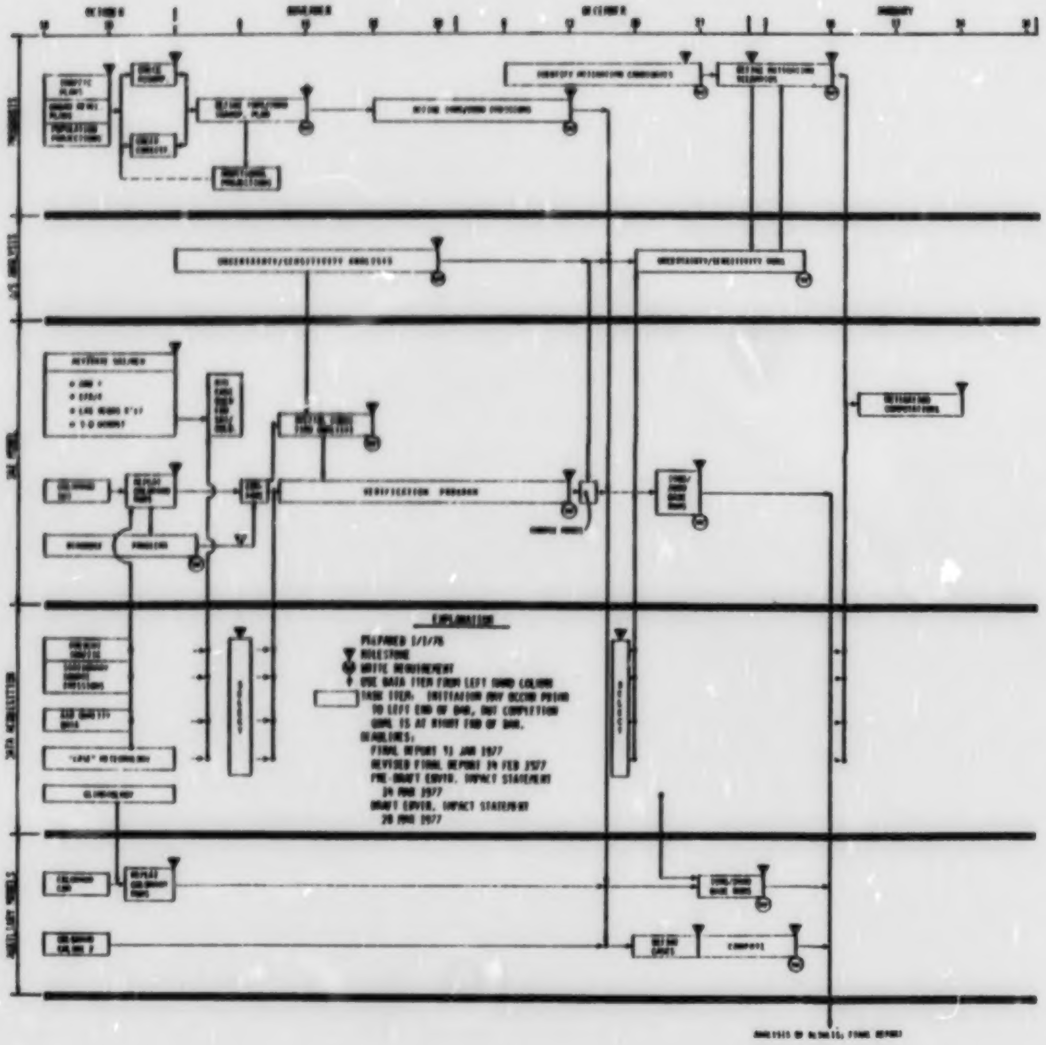
At the inception of this project, it was anticipated that planned growth, which presumed and required the support of the wastewater treatment facilities, would lead to unacceptable air quality in Denver for the time period up to the year 2000. This was expected to be true despite the adoption of the Denver Transportation Control Plan, which specifies measures that could be taken to improve air quality. Therefore, the original goals for this project involved the estimation of the sensitivity of air quality predictions to assumed physical conditions, to urban development policy options, and to potential mitigation measures. Achievement of these goals would provide the maximum guidance for land use planning, air quality planning, and choosing transportation control measures. This guidance would be of a general nature and would not presume particular solutions.

As discussed in this report, the results of the project did not support all of the expectations of unacceptable air quality. Particularly, it was found that, in terms of the ozone problem, Denver's air quality should steadily improve through the year 2000. Given planned growth and a fully effective Federal Vehicle Emissions Control Program (FVECP), the Denver region should experience much less severe violations of National Ambient Air Quality Standard (NAAQS) for ozone in 1985 than it does at present and probably none at all in 2000. This conclusion was not found to depend critically on elements of the Denver Transportation Control Plan, but achievement of FVECP hydrocarbon emissions reductions is essential and further reductions would lead to further air quality improvements.

These predictions of markedly improving air quality led to somewhat different emphasis on the goals and purposes of the project. The latter stages of the project focused less on the proposed measures for mitigating unacceptable air quality and more on substantiating the results and studying factors that might limit their validity.

C. STRUCTURE OF PROJECT AND REPORT

Completion of this project within the available time and effort was seen at the outset to depend on the availability and suitability of data, future plans, and previous modeling work. Thus, the first task of the project was to confer with the Denver staff of EPA Region VIII, the Colorado Division of Highways (CDH), the Air Pollution Control Division of the Public Health Department (APCD), the Regional Transportation District (RTD), and the Denver Regional Council of Governments (DRCOG) regarding their ability to supply these requirements. As a result of these discussions, a Project Performance Plan was developed, discussed with, and approved by the Project Monitor. A chart displaying the time and functional interrelations of the project elements is presented in Figure I-1.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FINAL REPORT 31 JAN 1977
REVISED FINAL REPORT 14 FEB 1977
PRE-DRAFT ENVIR. IMPACT STATEMENT 14 MAR 1977
DRAFT ENVIR. IMPACT STATEMENT 28 MAR 1977

FIGURE I-1. PROJECT PERFORMANCE PLAN

From Figure I-1 it may be noted that a major task was the activation of a new air quality model, the Denver Air Quality Model (DAQM), despite the availability of a previous version, the Air Pollution Simulation Program (APSP), which had already been applied to Denver air quality problems. The most important difference between the new version and the previous one is in the modeling of the atmospheric chemical reactions that lead to the production of ozone. The new chemistry (described in detail in Appendix A) reflects currently accepted concepts of ozone chemistry. The DAQM incorporating the new chemistry had not previously been applied in an air quality analysis, so a major portion of this project was devoted to a model validation study. Model results were compared with observed concentrations, and measures of model performance were, in turn, compared with performance measures for other oxidant prediction relationships and for models applied to other pollutants.

The remaining tasks shown in Figure I-1 reflect the purposes of the project described above and the housekeeping chores required to accomplish them. The tasks were directed toward the determination of:

> Present air quality in Denver with respect to relevant standards.

> Future air quality in Denver resulting from emissions estimates consistent with population, transportation, and activity patterns projected in regional plans.

> The effects of mitigation measures in easing anticipated unacceptable future air quality.

> The sensitivity of air quality predictions to major land use planning controls.

An additional task, the computation of the Denver population's exposure to and dosage of ozone during their daily activities, was added subsequently. Other tasks required to carry out these determinations were:

> Activation, testing, comparison, and/or selection of appropriate air quality models.

> Acquisition of air quality, emissions, and meteorological data, models, and future projections.
> Analysis of the assumptions and data that led to formulation of the projections.

The remainder of this chapter consists of discussions of modeling problems in general, and particularly with respect to Denver, and also brief descriptions of the elements of the project. Succeeding chapters contain in-depth discussions of and background material for each task of the project. The separate analytical efforts--validation, base case, sensitivity, mitigation, and exposure and dosage--are covered in Chapters II through VI. The appendices include material on the models used (App. A), the emissions data used (App. B), and the Denver regional planning processes (App. C).

D. AIR QUALITY MODELING

1. General Considerations

Air quality models are expressions of the principle of conservation of mass used to compute expected past, present, or future air quality. The principle of conservation of mass may be invoked on a regional average basis for a chosen time period or on subdivisions of the region or time period. For example, rollback models (De Nevers and Morris, 1975) treat regions as a whole for selected days and invoke mass conservation through a proportional relationship between the total emissions of a pollutant and the resultant atmospheric concentration. If the pollutant is not emitted, but rather is formed in the atmosphere (as is ozone), its concentration is assumed to be proportional to the emissions of its precursors. The EPA-recommended "Appendix J" oxidant prediction relationship (Schuck and Papetti, 1971) is of this nature.

A more precise conservation of mass concept is the removal of pollutant from the region by the wind. A model that treats this effect for a region as a whole is usually referred to as a box model (Hanna, 1971). At a finer scale, emissions from each source or block of sources may be taken as contributors to the pollutant concentrations in downwind sectors drawn from the sources. Since such sectors may overlap, better models may add contributions from all sources that affect each receptor location. Gaussian plume models such as the EPA-recommended Climatological Dispersion Model (CDM) and Air Quality Display Model (AQDM) are of this type (Khanna, 1976).

In the most detailed applications of mass conservation currently in use, variations of the winds, turbulence, and chemical reactions are accounted for at a resolution comparable to that of the emissions inventory. Since this resolution is typically provided by defining or computing the value of each variable at each node of a regular grid network, such models are called grid models. At present the EPA does not specifically recommend particular grid models for air pollution analyses, but it does recommend the use of the best available analytical tools for such studies. The SAI APSP and DAQM models, which have been applied to the Denver photochemical oxidant problem, are grid models.

The photochemical oxidant problem is exceedingly complex. The major oxidant of concern, ozone, is not generally emitted from man-controlled sources. Background concentrations of ozone from natural sources can be significant (Jerskey et al., 1976). It is generally recognized, however, that high ozone concentrations in urban airsheds are produced by chemical reactions in the atmosphere between oxygen, nitrogen oxides, gaseous hydrocarbons, and other less significant species (see Appendix A for a detailed discussion). The primary source of nitrogen oxides and hydrocarbons in urban airsheds is combustion, particularly in the engines of motor vehicles.

The primary oxide of nitrogen emitted from motor vehicles is nitric oxide (NO), which is subsequently oxidized to nitrogen dioxide (NO_2) in the atmosphere. In the presence of large amounts of NO (relative to NO_2), ozone concentrations are low. In an urban environment it typically takes from one to several hours for the NO_2/NO ratio to become high enough to permit formation of significant amounts of ozone. In such a time period, ozone precursors are likely to blow far from their sources and become dispersed. For this reason ozone concentrations are likely to be quite sensitive to regional wind patterns. In contrast, concentrations of nonreactive pollutants are often more clearly related to wind speed and direction near their source than to regional wind patterns. (Note this is also true of ozone precursors, but since little ozone is formed very near the sources, high ozone concentrations are not expected there.)

Models that do not take account of regional wind patterns are not expected to predict ozone patterns well; therefore, the use of grid-based physico-chemical models is recommended by SAI for the analysis of urban photochemical oxidant problems (see Roth et al., 1976). These models are complex, however, and simulating an entire year with such a model would be very expensive. For this reason it is difficult to contemplate their use for predicting annual average pollutant concentrations. Annual average air quality standards exist for NO_2 and particulates. Long-term average concentrations of these pollutants are generally analyzed using a Gaussian model such as the CDM or by simple rollback considerations.

Concentrations of particulates were analyzed with the CDM in this project. The CDM was also used as one indicator of possible NO_2 concentrations. It is very important to note, however, that most of the NO_2 in an urban airshed is not emitted, but is a product of chemical reactions just as ozone is. Thus the CDM, which does not treat chemical reactions assumes that all emitted NO is equivalent to NO_2. This assumption is probably valid at locations far downwind from NO sources, but it is clearly not even approximately true at the times and places for which maximum NO_2 concentrations were computed with the CDM. Calibration of CDM output is recommended by the EPA. If CDM output is multiplied by a factor to give an annual average NO_2 concentration equal to an observed annual average at a monitoring site, then the CDM output is adjusted to be correct at that monitoring site during the calibration year. CDM output is almost certainly in error for other locations and may be in error for other times. Although the CDM was used in this program as one tool to analyze NO_2 concentrations, the above concern is noted in the discussions in Chapters II and III. NO_2 concentration estimates from DAQM and Rollback are also presented in Table III-3.

2. Characteristics of the Denver Region

Denver has an air pollution problem. Exceedances of NAAQS have been measured for ozone, CO, and particulates since measurements at the Continuous Air Monitoring Program (CAMP) site in the downtown Denver began in 1965 or 1966 (Larsen, 1971). The annual average NO_2 concentrations at the same CAMP site have been observed to be near the NAAQS. Denver also have the typically dense emissions pattern of an urban region dependent on an automobile commuting life style. Denver is particularly lavish with the use of the automobile; according to the DRCOG estimates, the commuting auto fleet consists of 90 cars for every 100 commuters.

a. Climatology and Meteoroiogy of the Denver Region

Denver's climatology is unique for any city in its size category. According to Holzworth (1972), no city studied larger than Winslow, Arizona had, on an annual average basis, a morning mixing layer as thin as Denver's. Thus the pollutants emitted in the morning rush hour can be expected to be trapped in a very thin layer. Conversely, no city studied larger than El Paso, Texas had a mean afternoon mixing layer as thick as that of Denver. Thus Denver's pollutant cloud is usually very concentrated in the morning, but highly dispersed by early afternoon.

Because Denver is on the east side of the Rockies, the prevailing westerly winds do not result in containment of a pollutant cloud. The nearby mountain slopes, however, provide a typical upslope-downslope (drainage) diurnal wind pattern superimposed on other effects. Eddies generated by the interaction of stable winds with mountain ridges and canyons produce complex wind patterns.

Denver's summer season, which has the highest ozone concentrations, has wind patterns qualitatively similar to those in its winter season, which has the highest CO concentrations. Mixing layers are thinner in winter however. In spite of this, in this project, minimum mixing layer thicknesses in the central business district were assumed to be the same winter and summer. This was assumed because the high-rise buildings in this area generate turbulence related to their size in both summer and winter in very stable winds.

These complexities of Denver's meteorology and climatology ensure difficulty in defining windfields for input to a grid model. The CDM model used to analyze annual average concentrations of particulates and NO_2 invokes the assumption that complex wind patterns are smoothed by the annual averaging and only regional mean wind speed and direction are significant. Wind patterns are required for DAQM simulations. Surface wind observations were available from about two dozen stations for each hour of the day, but surface wind speeds and directions were needed for each of 225 grid cells covering the modeling region (see the grid description in Appendix A). The wind stations are not uniformly spaced; therefore substantial areas of the grid are far from any station. The array of stations is shown in Figure I-2.

Conventionally, wind values in grid cells are interpolated from station observations. Interpolation was used in this study because no alternatives were feasible, but reservations are noted:

> Large scale eddies drifting across the region can cause differences in the winds between stations that are greater than the differences in the observations.

> Hills and valleys (i.e., "topography") can guide the air flow so as to vary wind speed or direction greatly between wind stations. There are no wind stations in the mountains near the western edge of the modeling region, so winds extrapolated in that area are very suspect.

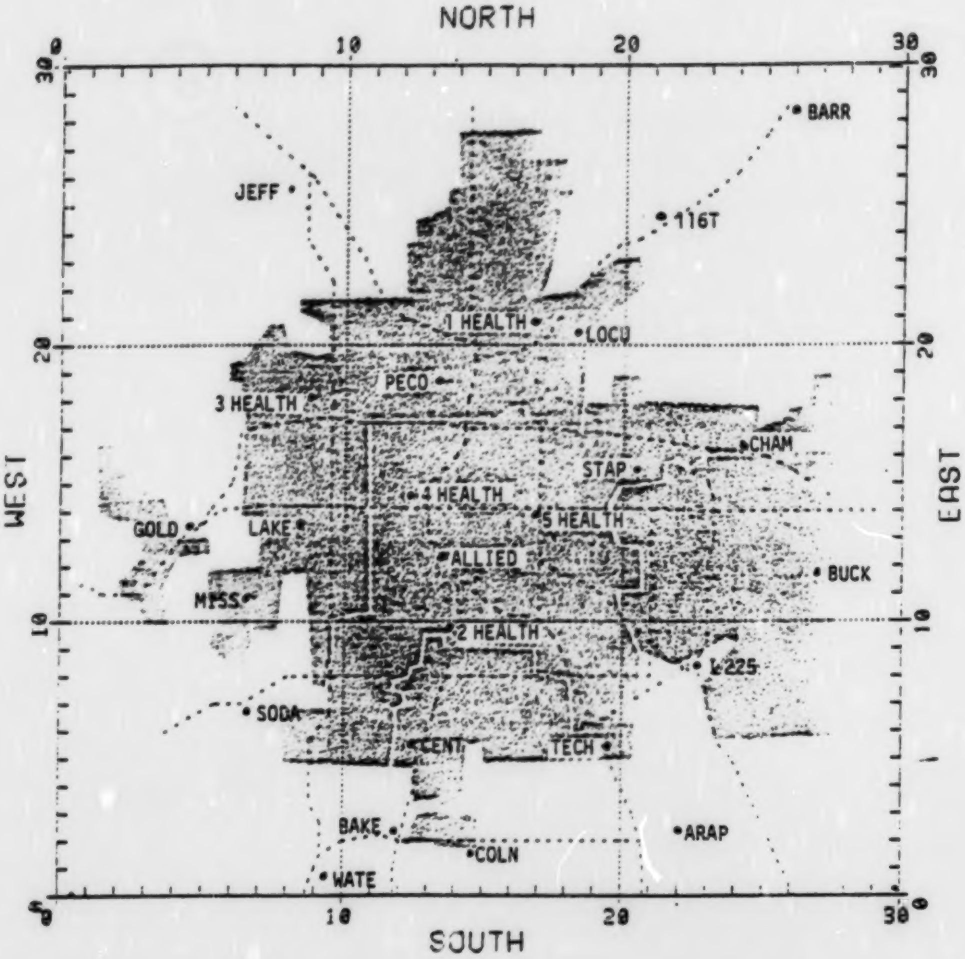
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FIGURE I-2. MAP OF DENVER AIR QUALITY MODELING REGION SHOWING WIND MEASUREMENT STATIONS

- The rules used in the DAQM for interpolation and extrapolation have little physical justification.
- Even small errors in wind speed or direction can add up to large errors in position for long path lengths.

Estimation of winds in the upper cells of the three-dimensional grid and estimation of mixing depths both depend on meteorological observations aloft. The only available observations aloft were from rawinsondes (radio wind sounders, balloon-borne transmitting packages) released twice a day from Stapleton Airport. These observations have less accuracy than desired, do not provide observations of daytime variations in the upper-level winds and mixing depths, and do not provide information on horizontal variations. In the absence of better data, upper winds were assumed to have the same patterns as the (interpolated) surface winds. Also the mixing depth was assumed to be constant in space over the modeling region; its temporal variation was inferred from the early morning rawinsonde release and hourly surface temperature measurements.

b. Available Air Quality Data

Air quality data are required for several modeling purposes. Atmospheric concentrations of the pollutants being studied must be available for model validation comparisons. Initial concentrations of all species that participate in the atmospheric chemical reactions must be specified so that model computations can begin with some known state. Similarly, the concentrations of all species must be specified at each upwind edge of the region (i.e., inflow boundary) and at the top of the modeling region.

For the three days chosen for the model validation and base case studies, the available air quality data consist of

Oxidants and Precursors

- Ozone measurements at nine stations (see Figure I-3).
- Total hydrocarbon measurements (i.e., reactive components plus methane) at six stations; methane measurements at

KEY

NG - Northglenn
WE - Welby
AR - Arvada
CR - C.A.R.I.H.
CM - Continuous Air Monitoring Program [CAMP]
NJ - National Jewish Hospital
GM - Green Mountain
OV - Overland
PR - Parker Road

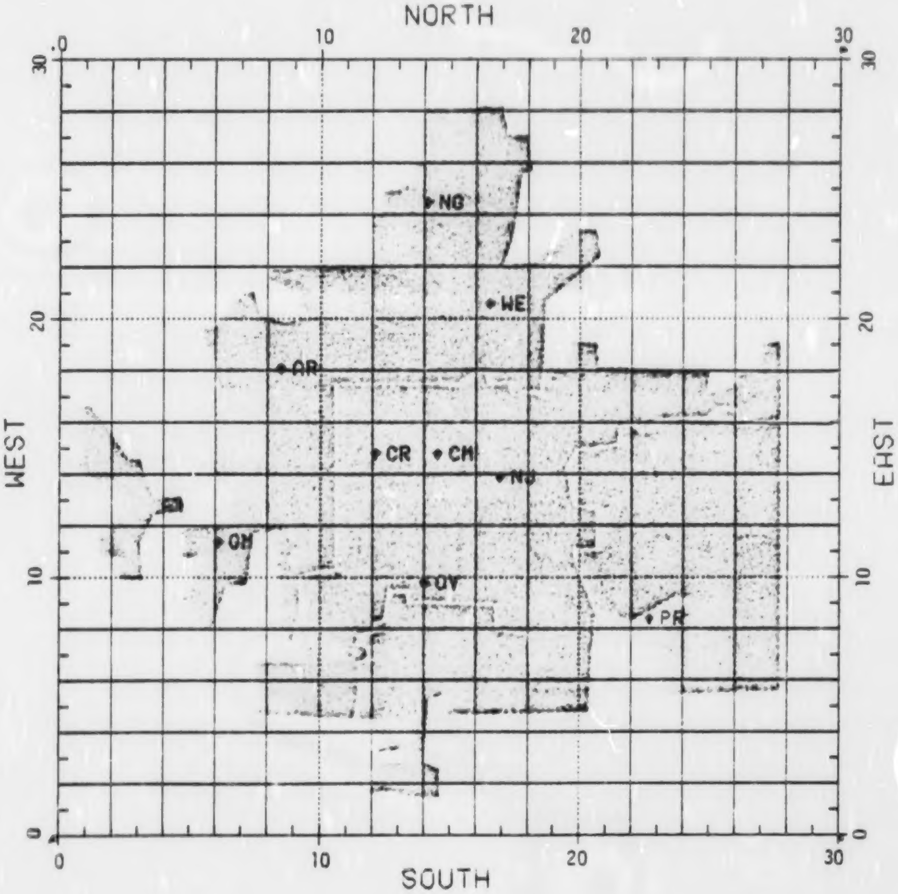
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FIGURE I-3. MAP OF DENVER AIR QUALITY MODELING REGION SHOWING 15 x 15 MODELING GRID OF 2-MILE SQUARES AND AIR QUALITY MONITORING STATIONS

one station. Concentrations of particular hydrocarbon species were not available.

> Nitrogen oxide and nitrogen dioxide measurements at one or two stations.

Other species

> Carbon monoxide measurements at nine stations.

These measurements are adequate only for validation comparisons. The need for initial and boundary concentrations cannot be met with these data. Therefore it was necessary to assume uniformity or simple patterns of initial and boundary concentrations. Because of this shortcoming, test runs were made with different assumed initial and boundary concentrations of the required species. Test results (see Appendix A) show that, for variations of initial and boundary concentrations within probable limits, subsequent predicted maximum ozone concentrations vary by only one or two parts per hundred million (pphm). Thus the shortage of measurements for initial and boundary concentrations seems not to have been critical.

c. Air Quality Climatology

The climatological characterization of the Denver region and the shortcomings in air quality data are connected. The reason for the insensitivity of peak ozone concentrations in Denver to the initial concentrations of ozone precursors appears to be the extreme shallowness of the morning mixing layer. The large emissions in the morning rush hour are trapped in this layer and lead to such high pollutant concentrations that the fraction due to initial material is negligible.

The other striking feature of Denver climatology, the rapid thickening of the Denver mixing layer during midday, is reflected in the early and sharp peaking of ozone concentrations. The thickening of the mixing layer dilutes the "ozone cloud" (i.e., the atmospheric volume with the highest ozone concentrations) rapidly so that ozone production later in the afternoon does not result in increased ozone concentrations.

Similar reasoning suggests an insensitivity of the results to boundary concentrations, except in situations where ozone or precursor concentrations on an upwind boundary are large. Pollutant concentrations at the boundary are apt to be large only when the region's ozone cloud reaches a boundary. This is then, by definition, a downwind boundary.

From the meteorology on the days studied in this project, it appears that wind reversals during midday hours can bring a portion of the ozone cloud back over a boundary it has already crossed. This situation cannot be treated correctly by the Denver Model since pollutant concentrations change by unknown amounts outside the modeling region. It is likely however, that the ozone cloud is produced mainly from material emitted in the morning rush hour in Denver's central business district. This material will take some time to reach the boundary of the modeling region. Given the rapid thickening of the mixing layer, dilution is likely to be far advanced by the time reentry occurs. While the possibility exists that days could occur when the characterizations above are not valid, the situation described is consistent with maximum ozone concentrations observed.

The afternoon mixing layer is typically quite thick, as noted above. This, together with the lack of any topographic barriers to the east and north, which are both downhill and downwind in a nighttime drainage flow, make the carry-over of pollutants from one day to another exceedingly unlikely. This conclusion is reinforced by the observation that peak ozone days occurred singly in the monitoring program during the summer of 1976 (Colorado Department of Health, 1976a).

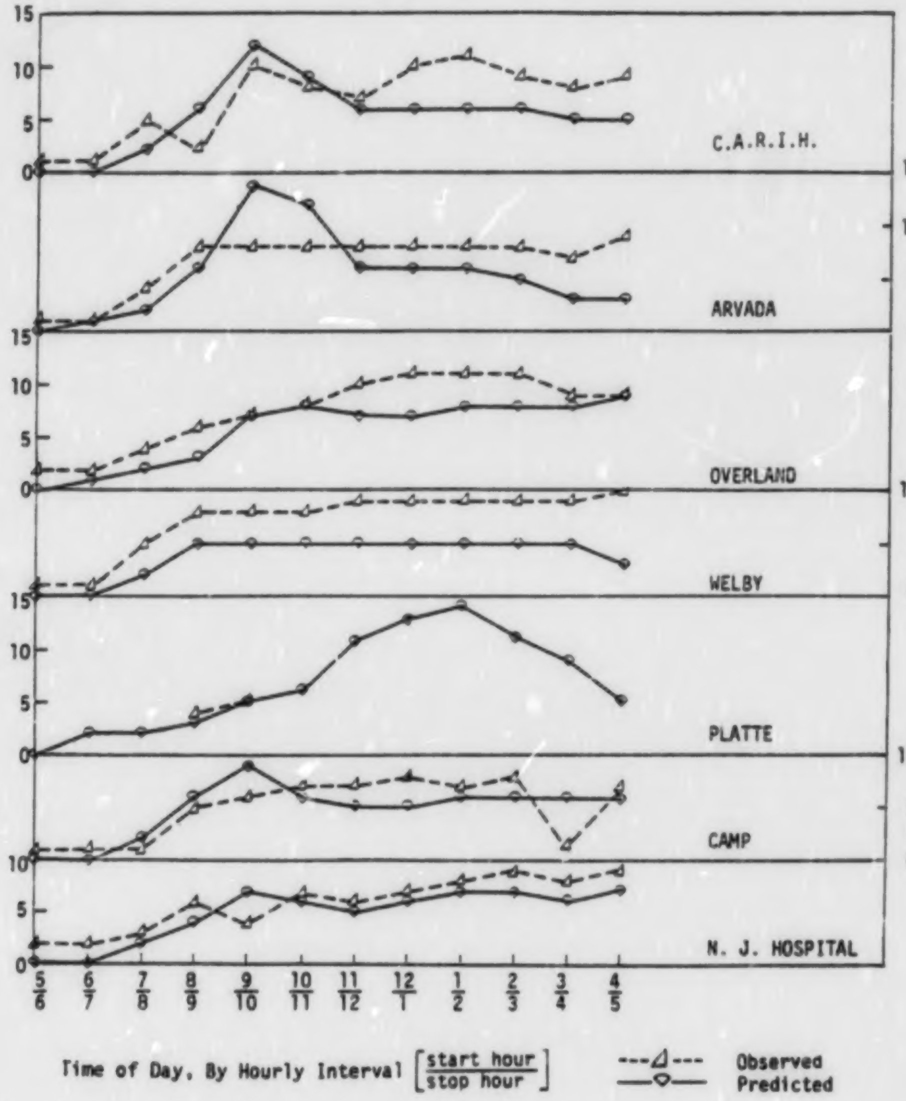
E. MODEL VALIDATION STUDIES

The DAQM was exercised for three summer days, 29 July 1975, 28 July 1976, and 3 August 1976. These were the only days for which meteorological data were available to run the simulations and for which air quality data were available to compare with the results. The 1975 day did not have one of the highest ozone concentrations in that year, but a significant violation (11 pphm) of the ozone standard (8 pphm) was observed. The second (17 pphm) and third (16 pphm) highest ozone observations of 1976 were on the two days of that year that were simulated.

Nearly 300 comparisons were made between one-hour-average ozone concentrations predicted for grid cells and observed in the atmosphere at corresponding points. These are shown in Figure I-4. Although there were substantial differences between predicted and observed concentrations on some occasions, on the whole good correspondence between them was noted. The differences were not so large as to permit distinction between errors in simulation and in observation (measurement). Therefore, the simulation errors are only bounded by the differences.

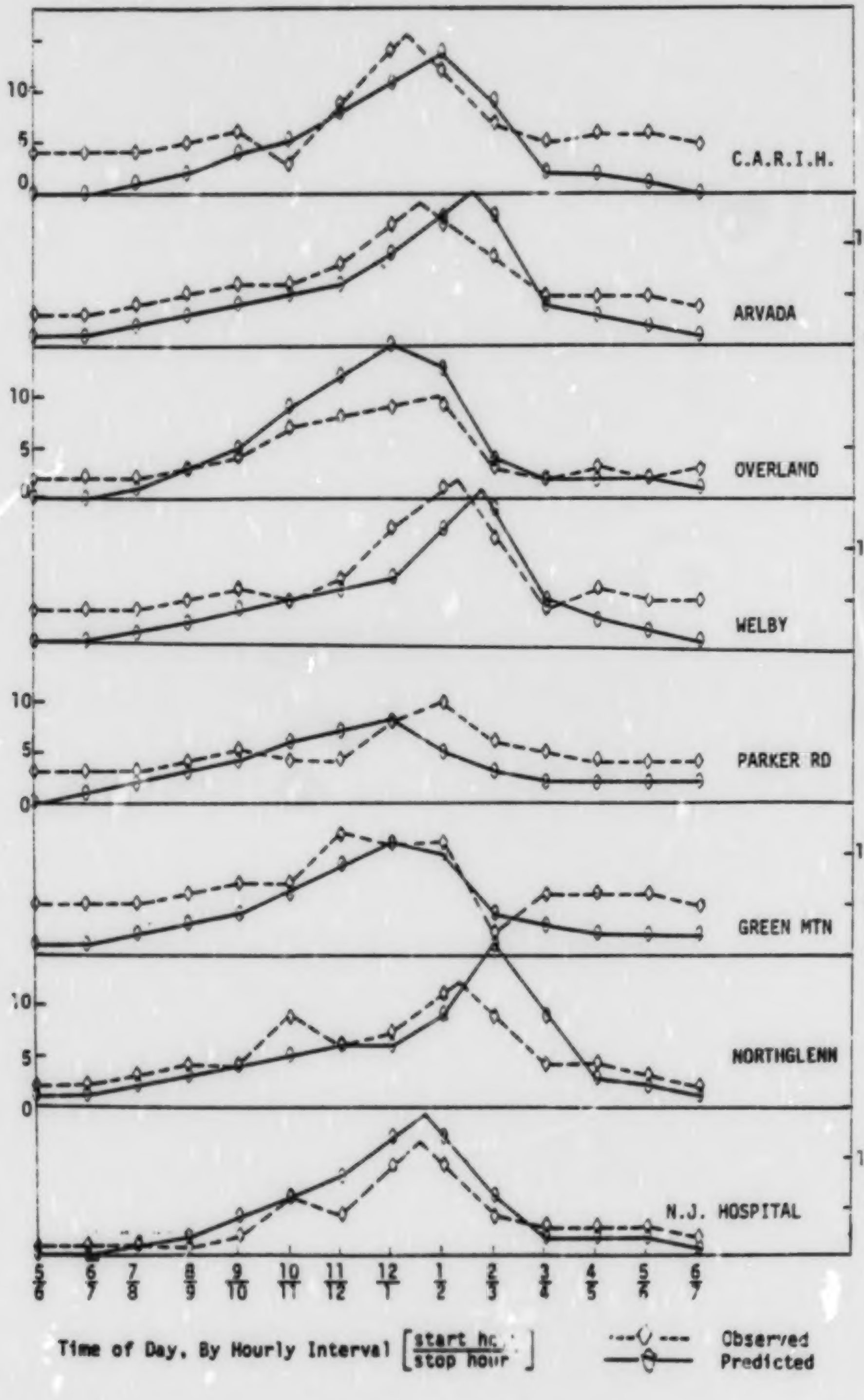
Predictions and observations were averaged separately for each hour at all stations, both for each simulation day and for all days (Figure I-5). The averages were examined for evidence of differences that would suggest correctable error in the formulation of the model. The averaged predictions were lower than the averaged observations early in the morning and late in the afternoon. As discussed in Appendix A, this effect may be due to microscale features of the thin mixing layers that occur early in the morning. Afternoon discrepancies may, on occasion, be due to the inability of the model to keep track of pollutant material that has left the modeling region and subsequently returned. In any case both the predicted and observed ozone concentrations are very low on the early and late occasions for which the noted bias exists. Therefore the bias does not appear to be the result of systematic error in chemical computations.

After completion of these analyses, we obtained evidence (Anderson and Blumenthal, 1976) that background ozone concentrations much larger than assumed here occur commonly in Denver. Use of 4 pphm as a typical value would substantially improve DAQM performance for early and late hours, but would have little effect on predicted peak ozone concentrations.



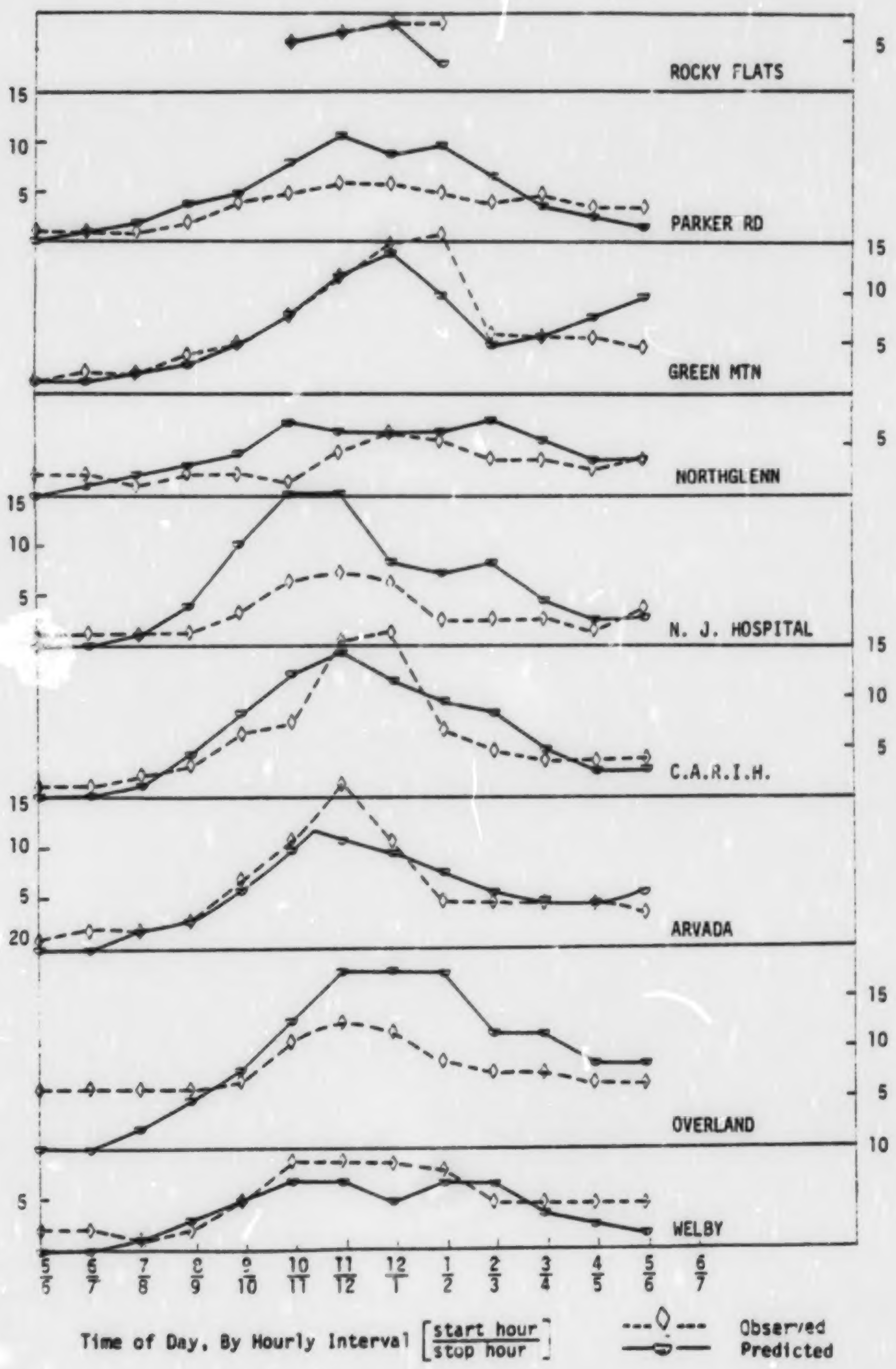
(a) 29 July 1975

FIGURE I-4. OBSERVED AND PREDICTED HOURLY OZONE CONCENTRATIONS (pphm) AT VARIOUS STATIONS



(b) 28 July 1976

FIGURE I-4. (Continued)



(c) 3 August 1976

FIGURE I-4. (Concluded)

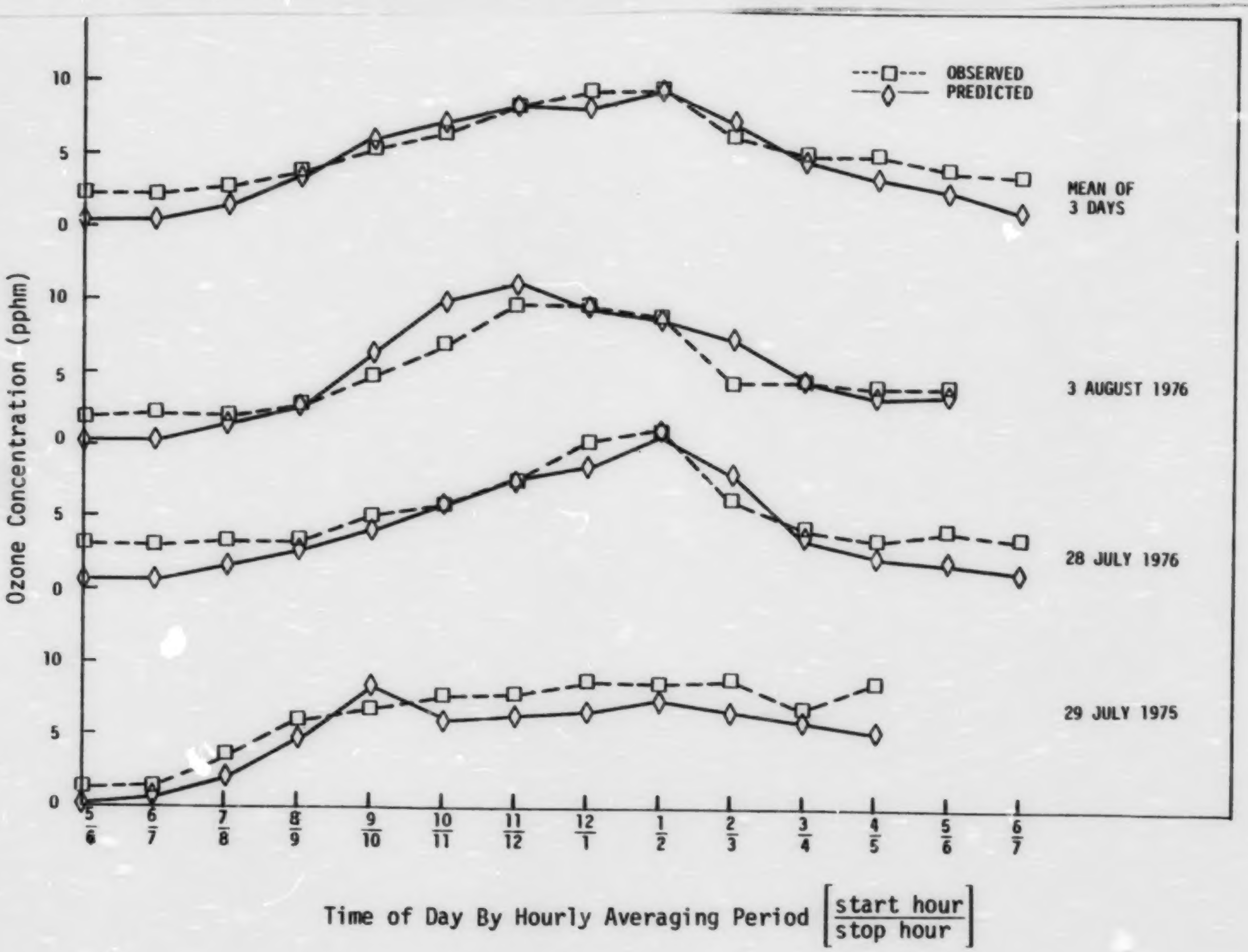


FIGURE I-5. VARIATIONS OVER ALL STATIONS OF OBSERVED AND PREDICTED AVERAGE OZONE CONCENTRATIONS

Averaging differences does not reveal any significant bias during hours of peak ozone concentrations. This finding is also confirmed by the results shown in Figure I-6. In this figure, the fractional mean deviation from perfect agreement between predictions and observations is shown to vary randomly at the higher ozone concentrations. The mean deviations are not negligible, but they are not excessive and both positive and negative differences occur.

Predicted and observed concentrations of carbon monoxide were also compared. Carbon monoxide is effectively an inert pollutant. Its major source is motor vehicle exhaust. Thus it is primarily emitted along roadways. The comparisons showed outstanding agreement at some stations and very poor agreement at others. This performance is consistent with the well-established microscale variability of roadway CO. The variation of the CO concentration from one side of a downtown city street to the other may well be from one to several hundred percent. The extremely good CO correlation at some stations is taken to represent the typical performance of the DAQM on a grid-cell-average basis (see the discussion in Chapter II).

DAQM validation statistics were compared with statistics published by the EPA (Turner et al., 1973) for annual average computations with models EPA recommends for use with nonreactive pollutants (Table I-1). Although averaging over a year should improve statistics, measures for DAQM's one-hour-average results exceeded those for the EPA models.

No validation was carried out for the application of the CDM to estimate annual average concentrations of NO_2 and particulates, since it was in use and had been calibrated by Colorado state agencies. As discussed in Chapters III and IV, neither calibration nor validation are appropriate concepts for these NO_2 studies since comparison data are only available from a single station in the central business district. At that station we judged that the uncalibrated predictions were in error by substantially more than they were in outlying regions, where high NO_2 concentrations are more likely.

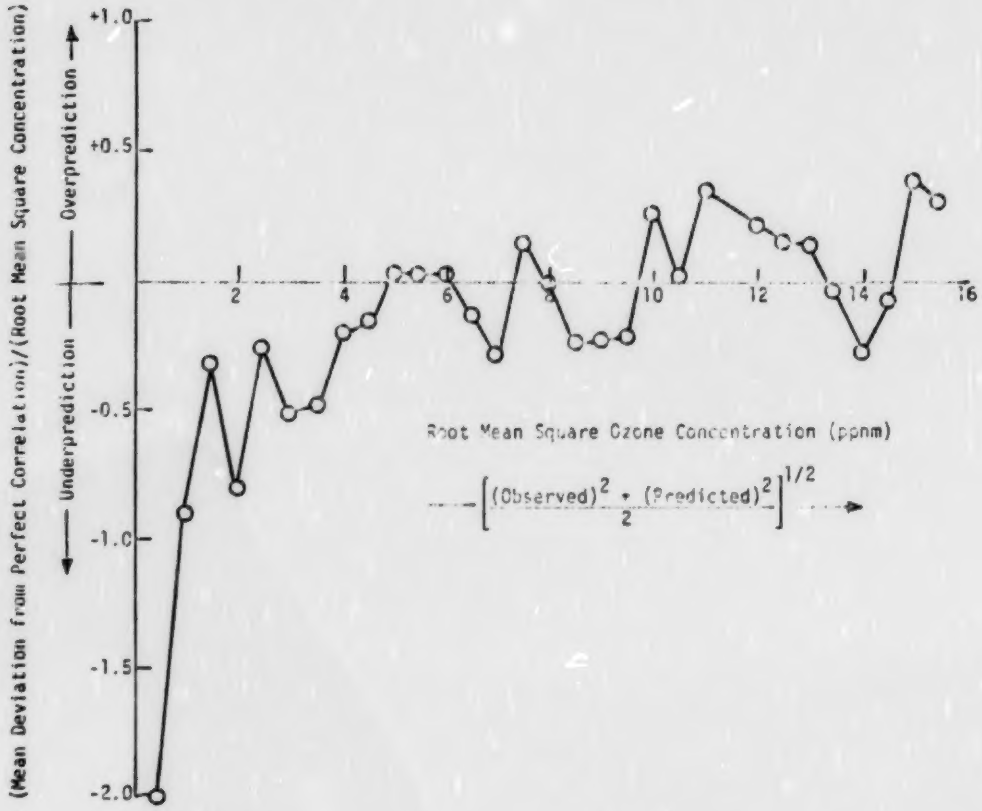


FIGURE I-6. ESTIMATE OF BIAS IN MODEL PREDICTIONS AS A FUNCTION OF OZONE CONCENTRATION

TABLE I-1. VALIDATION MEASURES OF VARIOUS MODELS

[differences = (predicted-observed)/observed]

	Number of Comparisons	RMS Difference	Mean Absolute Difference	Lower Limit Difference	Upper Limit Difference	Difference Range
SO_2 Annual Averages*						
AQDM	75	0.90	0.68	0.64	2.30	2.94
CDM	75	0.39	0.27	0.87	1.23	2.10
Gifford (box)	75	0.61	0.53	1.30	0.22	1.52
Hanna (box)	75	2.44	1.32	1.07	9.13	10.20
Mean	75	1.08	0.70	0.97	3.22	4.19
O_3 Hourly Averages						
SAI Denver Model	279	0.31	0.35	0.90	1.16	2.06

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* SO_2 model measures were computed from data in Turner et al. (1973).

Calibration constants recommended by the APCD were used for particulates. The constants were such that 51 ppm background was to be added to 1.96 times the predicted concentration. This large a correction to CDM model results suggests substantial observational and/or emissions inventory problems.

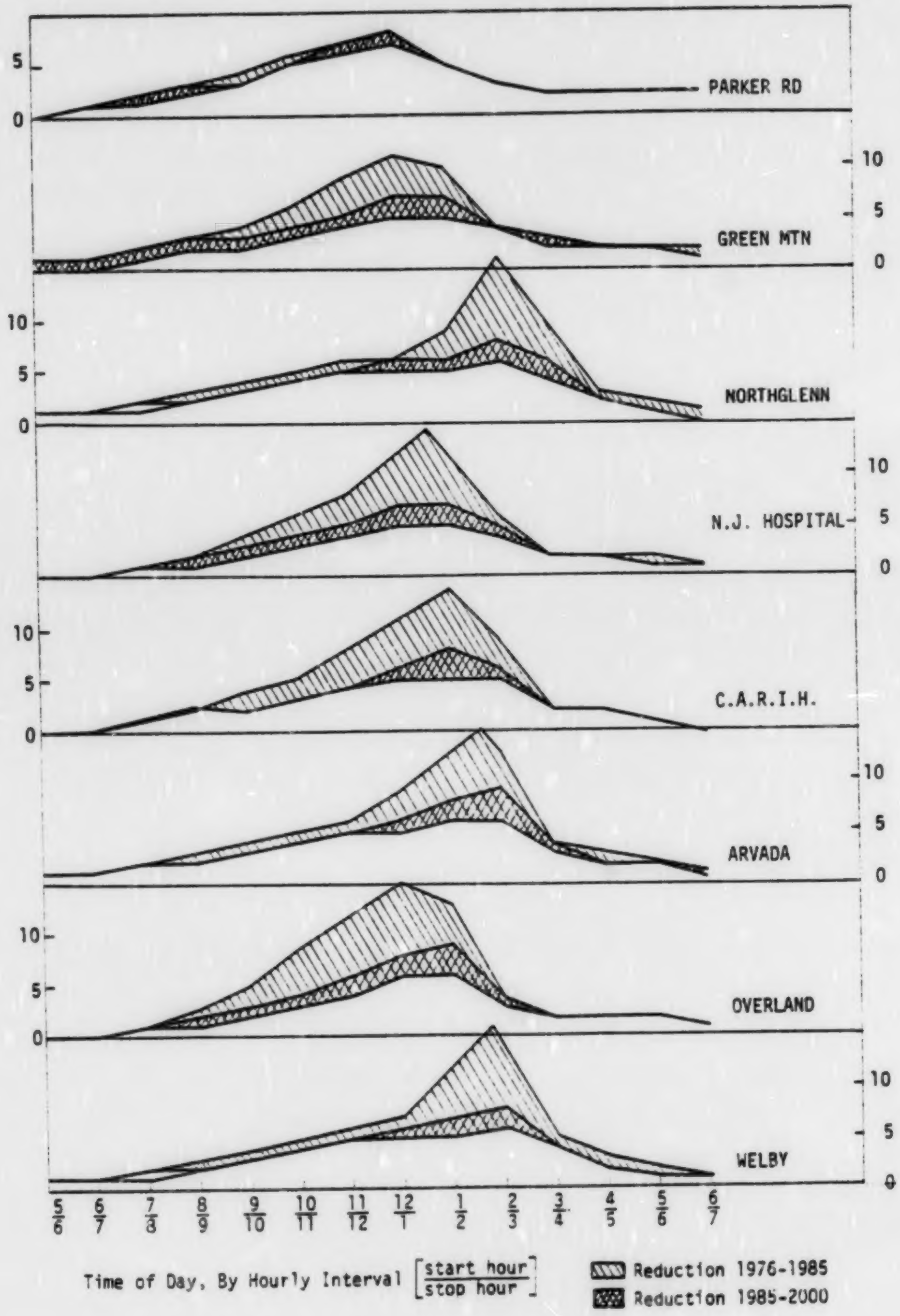
F. BASE CASE STUDIES

Estimates of present and future air quality in the Denver region were made from model computations using SAI's Denver Air Quality Model (DAQM) and EPA's Climatological Dispersion Model (CDM). Computations were made for comparison with each NAAQS. The DAQM, a "real time" model, was used to estimate the highest one-hour-average concentrations of ozone and carbon monoxide. CDM was used to estimate annual average concentrations of particulates. Annual average concentrations of nitrogen dioxide were inferred from both CDM and DAQM results.

1. Ozone

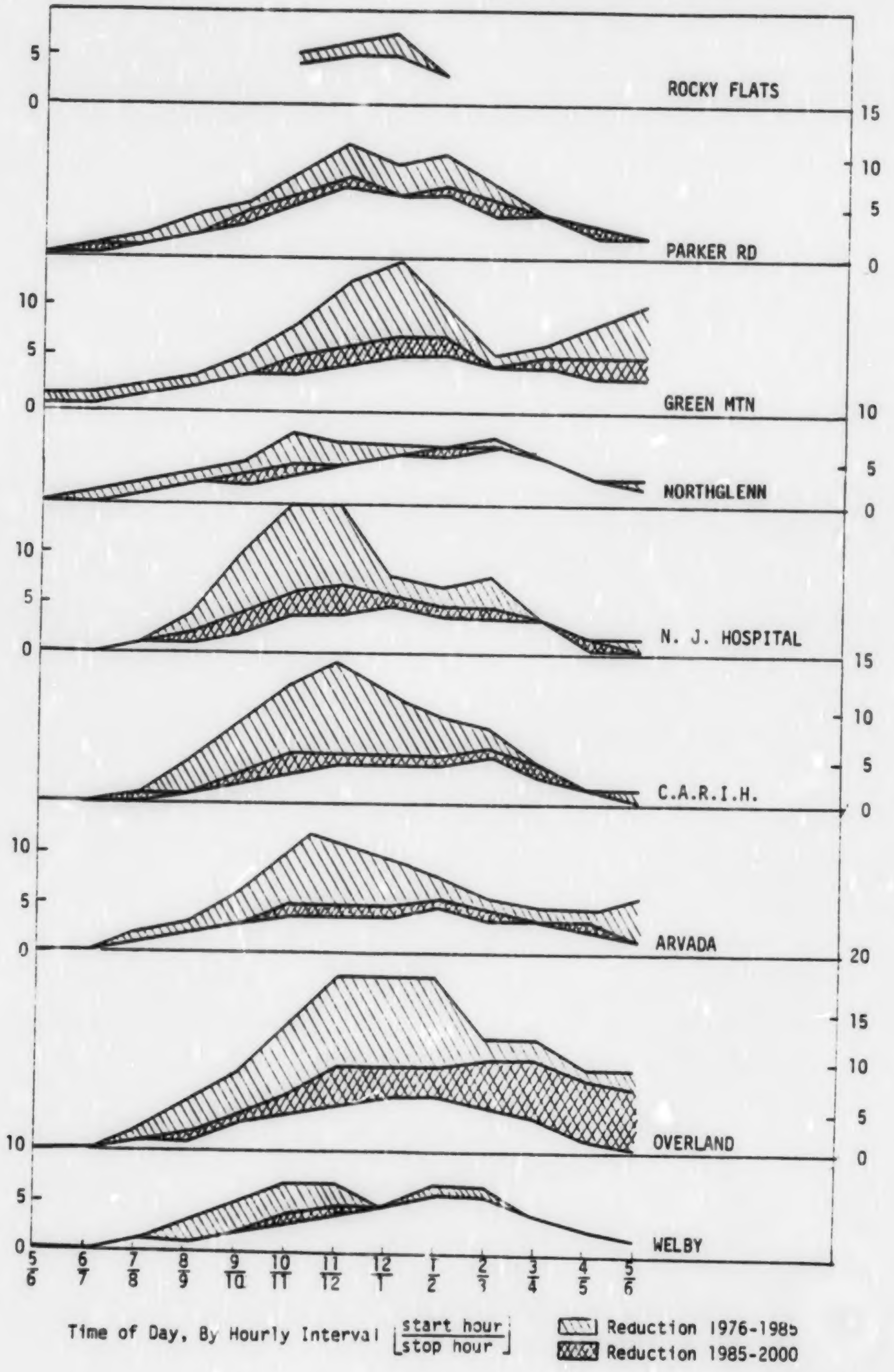
As described above, two of the three summer days for which data were available were reasonably representative of worst-case ozone episodes. Simulations with the meteorological conditions on the two days, 28 July and 3 August 1976, were made with current emissions inventories for the validation study. For the base case study, additional simulations were made with the same meteorological inputs, but with emissions data estimated to represent conditions in the years 1985 and 2000 (see Appendix C for details).

The simulations of air quality in future years compared with 1976 (see Figure I-7) show that in spite of population growth and growth in transportation, commerce, and industry, peak ozone concentrations are predicted to drop from 24 pphm in 1976 to 13 pphm in 1985 and 9 pphm in 2000, assuming strict compliance with the FVECP.



(a) Meteorology for 28 July 1976 Assumed

FIGURE I-7. REDUCTION IN PREDICTED OZONE CONCENTRATIONS (pphm) AT DENVER STATIONS DUE TO PREDICTED FUTURE EMISSIONS CHANGES



(b) Meteorology for 3 August 1976 Assumed

FIGURE I-7. (Concluded)

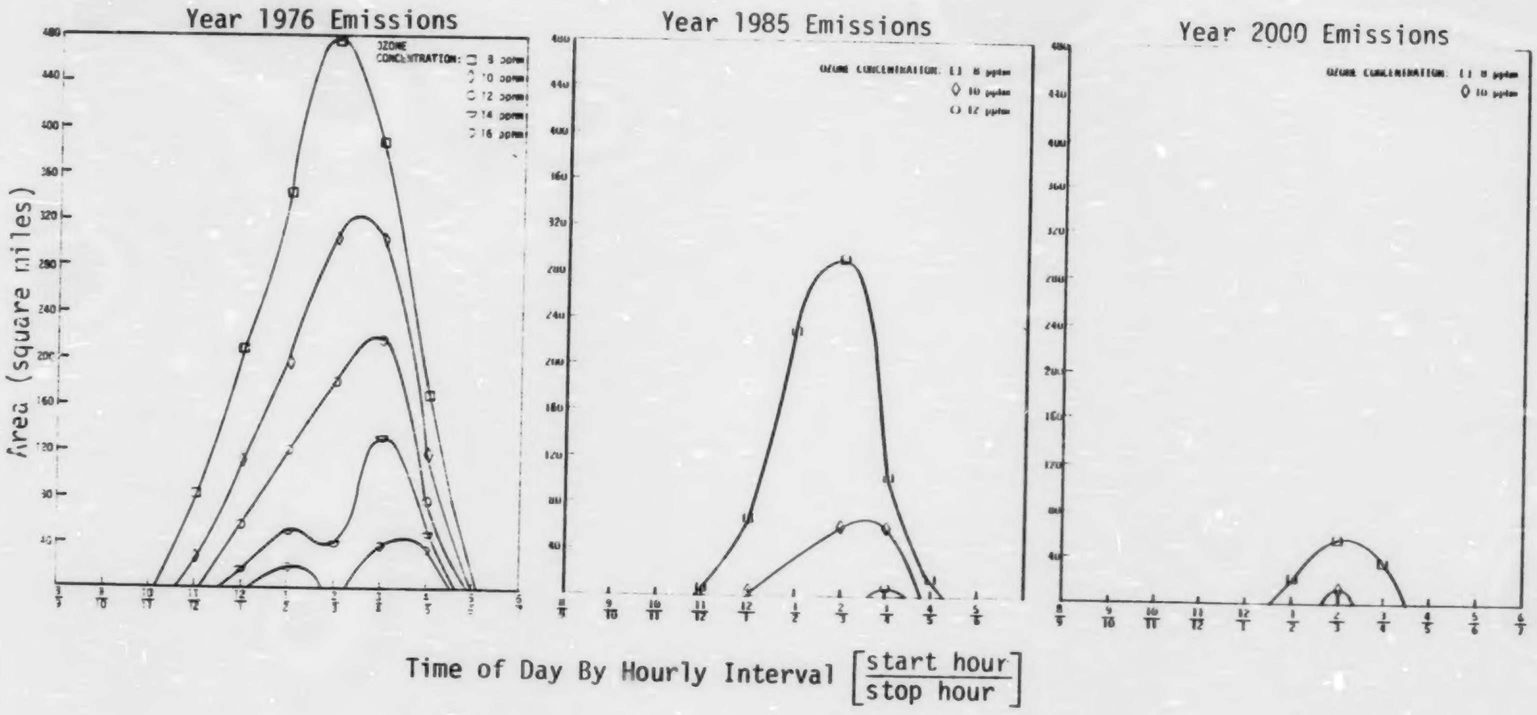
The emissions per vehicle mile traveled (VMT) of ozone precursors--hydrocarbons and nitrogen oxides--drop drastically by the year 2000 because of Federally mandated reductions in emissions from motor vehicles. The most significant reduction in peak ozone concentrations, however, occurs during the first period--1976 to 1985--when only hydrocarbon emissions are reduced. Reductions in NO_x emissions per vehicle-mile traveled are not expected to decrease the total NO_x emissions because of increases in VMT; but reductions in total HC emissions are expected from the Federally mandated HC reductions.

The results of the Denver model simulations also show that fractional decreases in the areal extent of NAAQS violations exceed the fractional decreases in peak ozone concentrations. In 1976, computed NAAQS violations (> 8 pphm taken as ≥ 9 pphm) occurred over a maximum of 300 to 400 square miles. By 2000 the area is expected to be reduced to 0 to 40 miles, although the predicted exceedance is so small that a violation cannot be confidently assumed (Figure I-8).

2. Carbon Monoxide

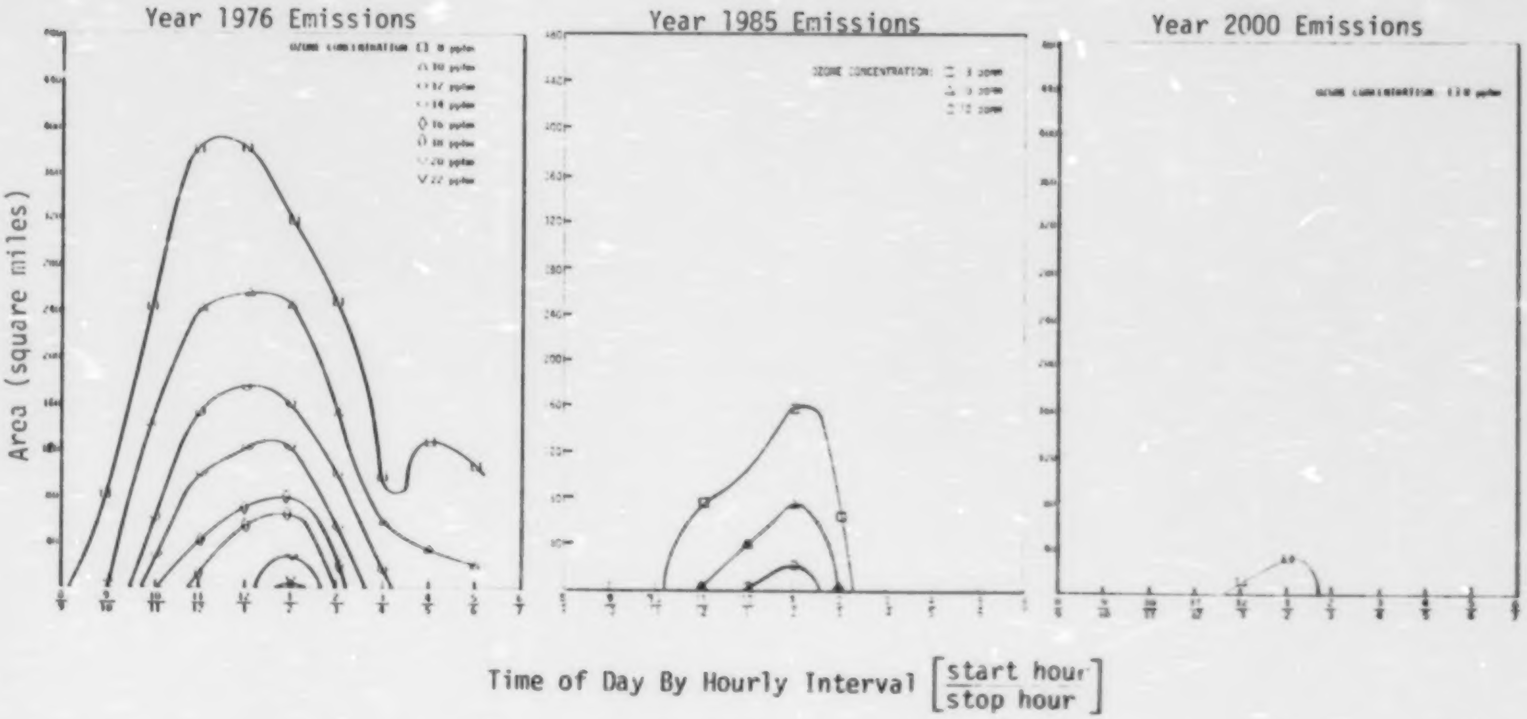
Carbon monoxide concentrations were computed with DAQM for a winter day, 15 November 1975. Winter days tend to have the highest concentrations of nonreactive pollutants because the low solar intensity permits the shallow morning mixing layer to last longer, and sunlight is not required for production of nonreactive pollutants. In addition, the late sunrise assures that the thinnest mixing layer will exist during much of the morning rush hour period.

Concentration gradients can be much larger for nonreactive pollutants than for ozone. This is because peak concentrations occur very close to sources (primarily traffic for CO) before dispersion dilutes the pollutant. As a result, the definition of peak concentrations of CO is very difficult. CO monitors on opposite sides of a heavily traveled street can easily show concentrations differing by a factor of two (or, in some cases, by an order of magnitude) (see Chapter II).



(a) Meteorology for 28 July 1976 Assumed

FIGURE I-8. SIZE OF AREA IN WHICH PREDICTED OZONE CONCENTRATIONS EXCEED GIVEN VALUES FOR YEARS 1976, 1985, AND 2000



(b) Meteorology for 3 August 1976 Assumed

FIGURE I-8 (Concluded)

The DAQM computation has a two-mile resolution and therefore microscale street effects are suppressed.

Under present conditions, CO concentrations in violation of the NAAQS can surely be found in any major urban area at particularly critical spots such as industrial, shopping center, or stadium parking lots or at busy intersections. This is certainly true in Denver, even though the DAQM predicts peak CO concentrations of 26 ppm for one hour and 15 ppm for eight hours (NAAQS are 35 ppm and 9 ppm, respectively). Since CO emissions are expected to decrease in the future (under the FVECP), one-hour violations are not predicted for 1985 and 2000 with DAQM. The predicted maximum one-hour-average CO concentrations for those years are 17 and 4 ppm, respectively. DAQM does predict a small eight-hour-average violation (10 ppm) in 1985, but none (3 ppm maximum) in 2000. The occurrence of violations in those years at "hot spots" will depend more on future vehicle emissions than on regional growth. That is, the number of vehicles in a parking lot should not change much, but the emissions per vehicle should decrease. The CO emissions at low speed (5 mph) are projected by the Federal Vehicle Emissions Control Program (FVECP) to drop by two-thirds from 1976 to 1985 and by an additional 50 percent from 1985 to 2000 (see Appendix B). From this it could be anticipated that many of the "hot spots" in the Denver region in 1976 will not produce NAAQS violations in those future years. Since the present hot spots have not been identified or monitored, this anticipation cannot be confirmed.

3. Nitrogen Dioxide

Estimates of NO_2 concentrations are very difficult to make. The primary emitted species is NO. Only 15 percent or less of the NO_x emissions are NO_2 (see Appendix B). There is no NAAQS for NO, however, and the only standard for NO_2 is on an annual average basis. After entering the atmosphere, NO is typically oxidized to NO_2 in the same set of photochemical reactions that generates ozone. During daylight hours, NO_2 photolyzes to regenerate NO. Because most NO eventually becomes NO_2, the typical NO_2 analysis involves not NO_2 but NO_x, under the assumption that all NO_x emissions are NO_2 (CDH, 1976). Since an annual average is desired, NO_x modeling was done in this project with the CDM.

While most NO is eventually oxidized to NO_2, all emitted NO_x is clearly not in the form of NO_2 at every position downwind of the NO source. The portion of NO_x that is not NO_2 is particularly high near NO sources. CDM can therefore be expected to seriously overestimate NO_2 concentrations in the densest source areas of a region. Raw CDM estimates should be more accurate near the periphery of the modeling region.

CDM is a calibrated model; that is, its results are multiplied by a factor to make them correspond with observations. The Denver region had just one NO_2 monitoring station, which was in the center of the densest downtown NO_x source area. CDM results were calibrated with data from this station; the CDM results for that station should be equivalent to the annual average concentration at that site for the calibration year. After calibration, the results from CDM should be progressively more in error (underpredicting) at greater distances from the calibration site. Since the emissions of all interacting species may change differently in the future, the calibration may not be valid for future years.

The problem of the complex photochemical reactions is resolvable by using DAQM; in fact, NO and NO_2 concentrations are computed by DAQM. This model does not, however, give annual averages. Peak one-hour-average NO_2 concentrations computed with DAQM for worst case summer days show decreases in NO_2 from 1976 to 1985 and again to 2000. This is in contrast to predictions of steady increases of NO_2 using the erroneous assumptions of CDM. It thus seems fair to conclude that:

> Observations show current compliance with the NAAQS standard of 5 pphm NO_2 on an annual average basis.

- > NO_2 concentrations may decrease from 1976 to 1985 and again to 2000 by the ratio of DAQM results for those years. They should not increase as much as was predicted by CDM.
- > Current modeling techniques are inadequate to produce accurate annual average NO_2 predictions.

4. Particulates

Annual average particulate concentrations were computed with CDM. The model results were calibrated with observational data. Since the data are collected with monitors usually located near major source areas (e.g., roads) the calibration tends to overestimate the regional average concentrations. This is not to say the observations are wrong, merely that they are not directly comparable with model results. It is probable that the particulate concentration estimates contained in Chapter III are overestimates. Nevertheless, the predicted concentrations are so high (four to five times the state standard) that current and future violations may be expected.

Particulate standards are violated in many areas throughout the United States, but monitoring, source identification, and size analysis problems are so great as to make appropriate response recommendations difficult. Common monitoring problems are sample flow variation and chemical reactions on the filter. Much of the particulate material comes from natural sources that are difficult to control, and often a large fraction of the material is in particles so large that they cannot penetrate deep into the respiratory system. Thus they have little physiological effect.

G. SENSITIVITY STUDIES

The base case projections described in the section above are estimations of the air quality that would result from predicted emissions. The air quality thus reflects growth projections for each community, plans developed for a transportation system to serve the communities' needs, and Federally mandated vehicle emissions reductions.

It is important to estimate not only the air quality consistent with expected development but also the changes in air quality that would be caused by major growth modifications. Such modifications might be chosen to achieve some goal or might occur because communities develop contrary to projections. To determine the sensitivity of air quality predictions to growth projections, model simulations were run with a series of hypothetical changes in projected emissions patterns as described in Chapter IV. The changes chosen were 25 percent emissions reductions in arbitrarily selected suburban communities or clusters of communities, or a 17 percent reduction (i.e., no growth) in future emissions in the city of Denver itself. In each case, emissions in the remainder of the region were raised uniformly to provide a constant regional emission rate. These changes are intended to represent larger, more isolated effects than are likely to be obtainable by deliberate policy decisions or are likely to occur in an uncontrolled course of events.

In spite of the drastic changes in emission patterns, the change in predicted ozone distributions was almost undetectable. Thus it does not seem likely that deliberate or uncontrolled redistribution of growth patterns could greatly affect peak ozone concentrations or ozone patterns.

The sensitivity of the ozone concentrations predicted by the Denver Model to the assumed degree of atmospheric dilution was also studied. Changes in meteorological input were made to represent the uncertainty in specifying worst-case meteorology. Lower average wind speeds or shallower mixing layers than originally estimated from data were used. Both these changes would produce less dilution and thus higher ozone concentrations than were computed in base case runs. Decreases of one-third in wind speed, mixing layer thickness, and in both wind speed and mixing layer thickness were assumed at each grid point. (Note that the proportional decreases preserve wind patterns.) The results of these simulations showed that a one-third decrease in wind speed had a negligible effect on the peak ozone concentration, but substantially increased the area in which the NAAQS was violated. In contrast, peak concentrations increased but areas did not when changes were assumed in mixing layer thickness. When both parameters were changed, the results changed by less than the product of the parameter ratios.

Simple "box model" analyses, which are often recommended for regional planning applications, would predict a 50 percent ozone increase for a 33 percent reduction in either wind speed or mixing depth. Ozone concentrations predicted by the Denver Model increased 4 percent for the one-third decrease in wind speed and 16 percent for a one-third decrease in mixing depth. If both wind speed and mixing depth are decreased by one-third, the box model predicts a 125 percent increase but the Denver Model shows only a 33 percent increase.

These results show that worst-case meteorology estimates would have to be in error by implausible amounts to invalidate the conclusions of the base case studies.

H. MITIGATION STUDIES

The final studies using model simulations were to determine the effectiveness of potential air quality mitigation measures. Although improved air quality in Denver was predicted by the base case studies, present air quality in Denver is seriously in violation of NAAQS, especially for ozone. Predictions in these studies show continued violations of particulate standards through 2000 and violations of ozone and eight-hour CO standards through 1985. Estimates of NO_2 concentrations vary from compliance to violation through the entire period. Although no projections were made past the year 2000, all projected vehicle emission factor reductions should be achieved by 1993. Thereafter increases in VMT may again increase ozone concentrations.

One major mitigation measure is strict compliance with FVECP standards, which was assumed for base case studies. Data from EPA

Region VIII indicate that compliance with the FVECP is unlikely without controls more strict than presently recommended inspection and maintenance programs. The assumptions of growth, transportation planning, and an effective vehicle emissions control program may not be realized. In such circumstances, the institution of further air pollution mitigation measures may become necessary. If so, it would be desirable to know how effective such measures might be and how much control might be required to achieve an air quality goal.

Simulations were made to address these questions. First, a simulation was made with a 30 percent reduction in emissions (from base case) in every grid cell. This reduction could represent one or a set of mitigation measures that apply proportionately to all sources. It would seem that 30 percent regionwide emissions reductions would be quite severe, and that larger reductions would be difficult to impose on a community. Simulation results show a reduction in peak ozone concentrations of 15 percent or less. Thus, if local mitigation measures need to be applied to achieve air quality goals, they will have to be severe to have a significant effect on ozone concentrations.

A second simulation indicates the much greater improvement in air quality possible with selective vehicle emission controls. Such controls would probably only be feasible by Federal mandate, since auto manufacture is not locally regulated except in California. The selective control simulation used relaxed NO_x emissions standards roughly corresponding to a proposal now before Congress to permit 1 gram per mile of NO_x emissions rather than the 1985 goal of 0.4 grams per mile assumed in the base case run. Results of this simulation for conditions otherwise the same as the 1985 base case run showed no violations of the NAAQS for ozone in the Denver modeling region. Note that this result is restricted to the modeling region. Relaxation of NO_x emission standards would increase NO_2 concentrations in downwind areas, possibly exacerbating air quality problems in those areas.

The reason for an improvement in air quality with increased NO_x emissions is that the ratio of the two ozone precursors (hydrocarbons and NO_x) becomes less favorable for ozone production. Not enough hydrocarbons would be present to oxidize the NO to NO_2 and thus stimulate ozone production before atmospheric mixing and dilution lowered all concentrations. Note that this result applies to summer days in Denver with worst-case meteorology (as do many other results in this report, to some degree). Regions with other emissions mixes or patterns and other climatology might experience other effects.

A final simulation involved studying the effects of noncompliance with FVECP (compliance was assumed in the base case). In this simulation, light-duty vehicle emission factors were provided by EPA Region VIII to represent vehicle emissions expected assuming the present limited effectiveness of controls and without the implementation of an inspection and maintenance program. Simulations of 1985 and 2000 base case runs with 0.4 and 0.9 grams per mile of NO_x emissions and with the new, degraded emission factors were made. Qualitatively, the results of these runs were similar to those of the base case, but the decrease in ozone concentrations was not as great. Figure I-9 shows predicted ozone peaks in each year for the base case and for noncompliance with the FVECP. Also shown is the predicted ozone peak for a uniform 30 percent reduction in emissions and for a 5 percent reduction in hydrocarbon emissions (estimated to be obtainable from the installation of vapor recovery devices on gasoline station delivery nozzles).

The lines of equal predicted ozone concentrations shown in Figure I-9 put predicted ozone peaks in perspective. They show graphically the complexity of the dependence of ozone concentrations on precursors. Note that compliance with the ozone NAAQS is not predicted by 2000 if FVECP is not followed. Peak ozone concentrations about 2 pphm higher than base case results are predicted. This is not a large absolute effect, but it is a substantial percentage change from the small concentrations predicted if FVECP is enforced. Vapor recovery at gasoline stations is shown to be an effective measure for achieving a small decrease in ozone concentrations.

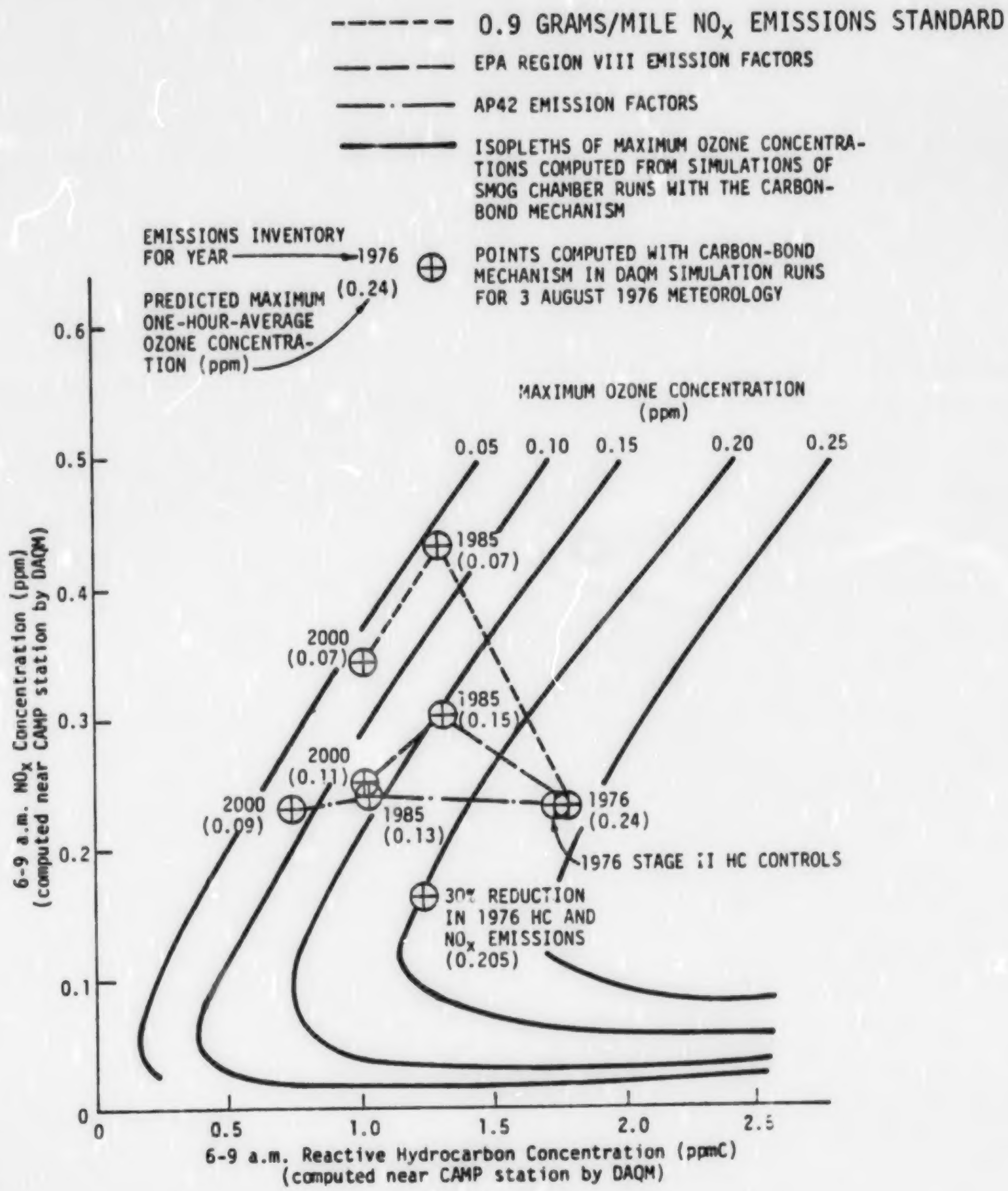


FIGURE I-9. MAXIMUM OZONE COMPUTED BY CARBON-BOND SIMULATIONS OF SMOG CHAMBER EXPERIMENTS AND BY DENVER MODEL FOR VARIOUS ASSUMED FUTURE EMISSIONS

In winter simulations, CO concentrations were found to be increased over that assumed in the base case analysis by 60 to 70 percent in 1985 and by 50 percent in 2000 by the degraded emissions factors. Thus, the eight-hour CO standard would not be met on even a grid-cell-average basis in 1985.

I. RECOMMENDATIONS

The results of this project show the critical importance of maintaining vehicle emission standards if predicted improvements in Denver's air quality are to occur. Although emission standards must be set by Federal mandate, realization of the benefits will also depend on a strong local vehicle inspection and maintenance program. If additional local mitigation measures are required, substantial across-the-board reductions of regionwide emissions will be necessary to have a significant effect on ozone concentrations.

Continued attention to collecting and improving emissions, air quality, and meteorological data bases is vitally important for further studies. Particularly useful additions to the data base would be data on hydrocarbon species emitted and more extensive observations of wind throughout the mixing layer and above and across the entire region.

It is suggested that further use of DAQM in the Denver region by contractor or by local agencies would be quite valuable. Attention should be given to shortcomings in modeling techniques for all pollutants, but particularly for NO_2. No suitable models are now available for estimating compliance with the annual average NAAQS for NO_2.

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II DENVER AIR QUALITY MODEL VALIDATION STUDY

The present study is the first application of SAI's Denver Model. Before relying on model predictions in simulations of future conditions for which no observations exist, SAI believes it would be very desirable to have at least some measure of the model's performance for situations where observations do exist.

The results reported here show that the Denver Model performs as well or better for one-hour-average ozone predictions as EPA models do for annual average SO_2 predictions. However, measurement of the Denver Model's performance is limited by uncertainty in available air quality observations. A true validation of an air pollution model would require comparison of its output concentrations against actually occurring pollutant concentrations. The Denver Model output is in terms of averages over grid cell volumes. Pollutant concentration averages at this scale are not directly observable, since instruments sense the concentration only within a very small sample of air. Values of "actually occurring" concentrations, averaged over appropriate volumes, cannot be perfectly determined: they can only be inferred by instrument observations of limited accuracy representative of small samples from a grid cell volume. Validation comparisons of model results versus observations must be considered, nevertheless, in the absence of direct comparisons of "observed versus true." "Model (predicted) versus true" comparisons must depend on generalized statistical information as to the "observed versus true" relationship.

Another concern in a validation exercise is to reveal individual aspects of the model's performance. For example, the ability of the model to simulate concentrati[illegible]xima, concentration patterns, and the location and orientation of those [illegible]erns may be considered individually.

This is particularly important in a model to be used for predictions of future air quality. In such an application, the driving conditions--emissions inventory, meteorology, etc.--are hypothetical. The results can be characteristic, at most, of the air quality on some specific future occasion.

Given the uncertainty of the hypothetical future conditions, it is not essential that a model be able to perfectly simulate observed past conditions. If errors are due only to errors in wind patterns, a model that could be depended on to predict concentration patterns equivalent in magnitude and shape but displaced somewhat might be very useful although validation comparisons at points in time and space might not be impressive.

In the validation program reported here, every attempt was made to examine all relevant issues--the standards of model performance, the reliability of observational data and the individual and statistical comparability of model output and atmospheric measurements.

A. SIMULATION CASES

The model simulations run for validation purposes were also used to evaluate critical Denver air quality situations. These purposes are consistent, since high ozone concentrations present the best test of the model's ability to simulate the production of ozone from emitted pollutants. Lower concentrations of ozone are not only less critical in terms of air quality but are also more apt to be dependent on subtle variations in background and to be less functionally related to reactions between emitted materials.

The data files provided by the Colorado Division of Highways and the Air Pollution Control Division of the Colorado Health Department are described in Appendix B. They include meteorological data for three high ozone summer days. The first of the three days, 29 July 1975, had been preselected and extra data were taken in anticipation of stagnation conditions and high ozone on that day. Although the ozone standard (8 pphm) was exceeded that day (11 pphm was observed), a frontal system moved through the Denver region during the day and air quality conditions did not become as severe as expected.

The remaining two days represented in the data set were selected by Colorado Division of Highways as high ozone days out of an extended period of intensive monitoring during the summer of 1976. The two days were 28 July 1976 and 3 August 1976. The peak ozone concentration measured on the 28th was 16 pphm (twice the standard) and on the 3rd it was 17 pphm. The peak ozone measured during the 1976 summer study was 18 pphm on 30 June, which was not a day selected for meteorological data collection.

These three days were the only days for which data were available to SAI for air quality modeling. The favorable validation results reported below may or may not be fortuitous, but they are based on the entire available data set.

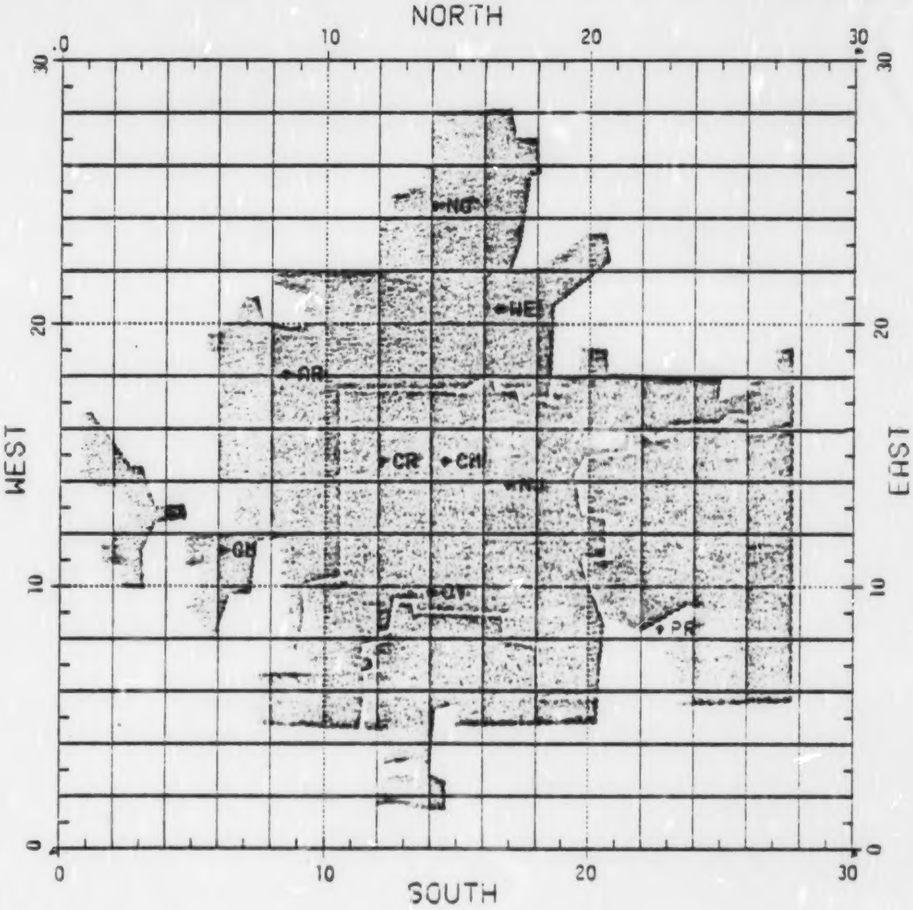
B. OBSERVATIONS AND COMPUTED RESULTS

The map of the Denver modeling region in Figure II-1 shows a 15 X 15 array of two-mile-square grid cells. All of the simulation results discussed here were obtained using this horizontal grid. The upper limit of the analysis region was the inversion base or 2500 feet above ground level, whichever was the lesser. The region was divided into three equal layers, but all results discussed here pertain to the layer adjacent to the ground.

Atmospheric ozone measurements were obtained at the stations indicated in Figure II-1. Generally, 24 one-hour-average ozone measurements were available for each station, but some data were missing. For the simulated hours, beginning at 5 a.m., six stations had complete data for 29 July 1975 and eight stations for 28 July 1976 and 3 August 1976. Similar data

KEY

NG - Northglenn
WE - Welby
AR - Arvada
CR - C.A.R.I.H.
CM - Continuous Air Monitoring Program [CAMP]
NJ - National Jewish Hospital
GM - Green Mountain
OV - Overland
PR - Parket Road


NORTH
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20
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WEST
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NG
WE
AR
CR
CM
NJ
GM
OV
PR
0
10
20
30
SOUTH

FIGURE II-1. MAP OF DENVER AIR QUALITY MODELING REGION SHOWING 15 x 15 MODELING GRID OF 2-MILE SQUARES AND AIR QUALITY MONITORING STATIONS

sets were available for carbon monoxide but only one or two stations reported NO_x data.

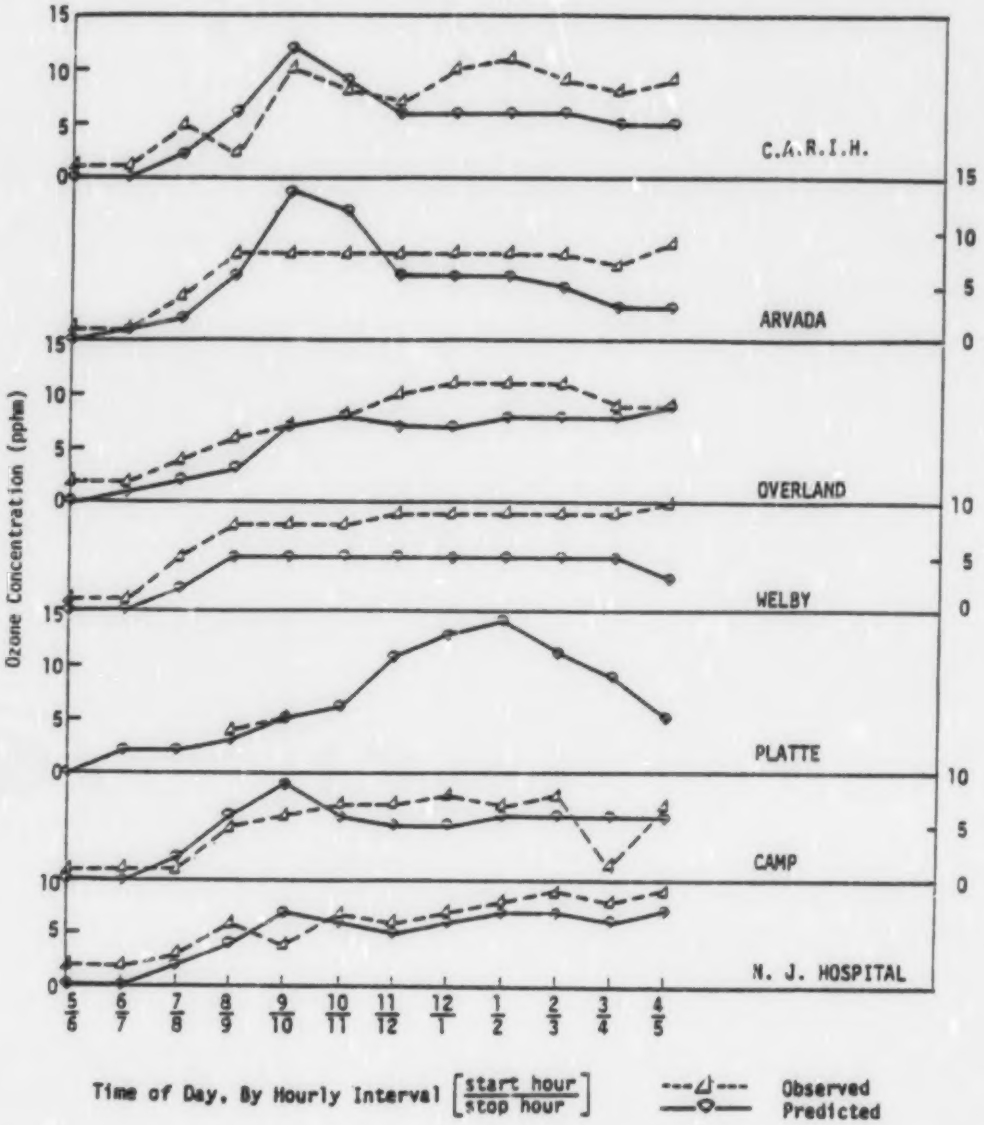
Computer results were printed out as arrays of grid cell concentrations (for the ground layer only) at each hour and also as one-hour averages. The one-hour averages are the only ones discussed here since they compare most directly with the atmospheric measurements. The result predicted by the model and used to compare with a station observation is the grid cell value for the cell in which the station is located. Use of this convention presumes that the predicted grid value represents the value everywhere in the cell to the degree of accuracy of which the model is capable. It does not represent a point value (e.g., at the cell center) of a continuous distribution. Thus, no interpolations were used to extract results at the coordinates of the observation stations.

C. VALIDATION RESULTS

1. Comparisons of Ozone Predictions and Observations

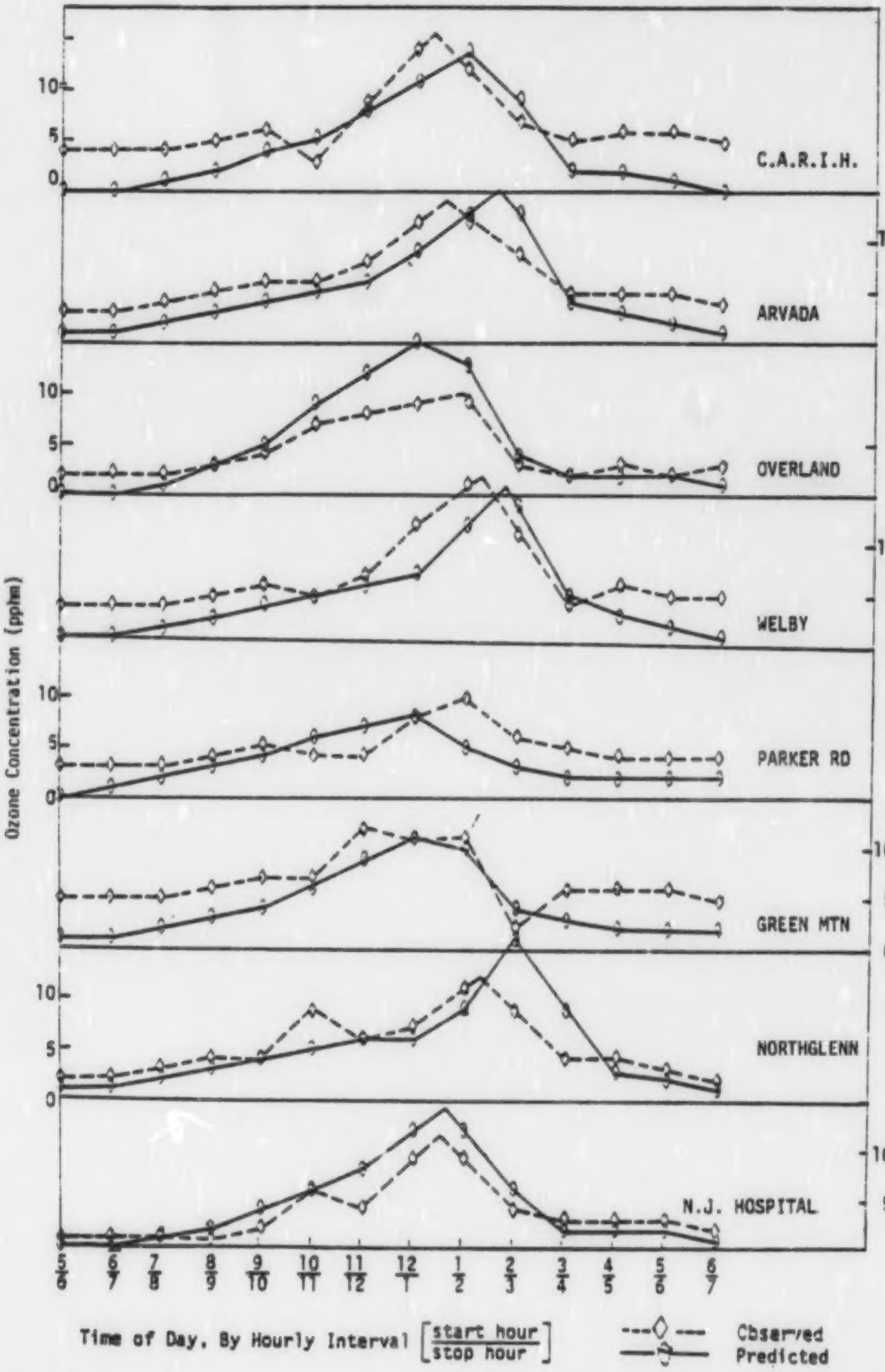
Predicted and observed ozone concentrations for each of the three days modeled are plotted versus time in Figure II-2. These comparison plots show good general agreement although small differences between predictions and observations occur on many occasions and substantial differences occur on some occasions. Specific phenomenological explanations cannot be identified for particular discrepancies, but some circumstances that could produce the differences shown are known for early morning, midday, and afternoon periods. These are described below.

Differences between predictions and observations near the start of the simulation period are to be expected. At this early time of day, measured values of ozone are always small and are in the range where instrument errors can easily exceed 100 percent [See the full discussion of ozone monitoring problems in Burton et al. (1976)]. Ozone trapped in a lowering inversion on the previous afternoon could be present in



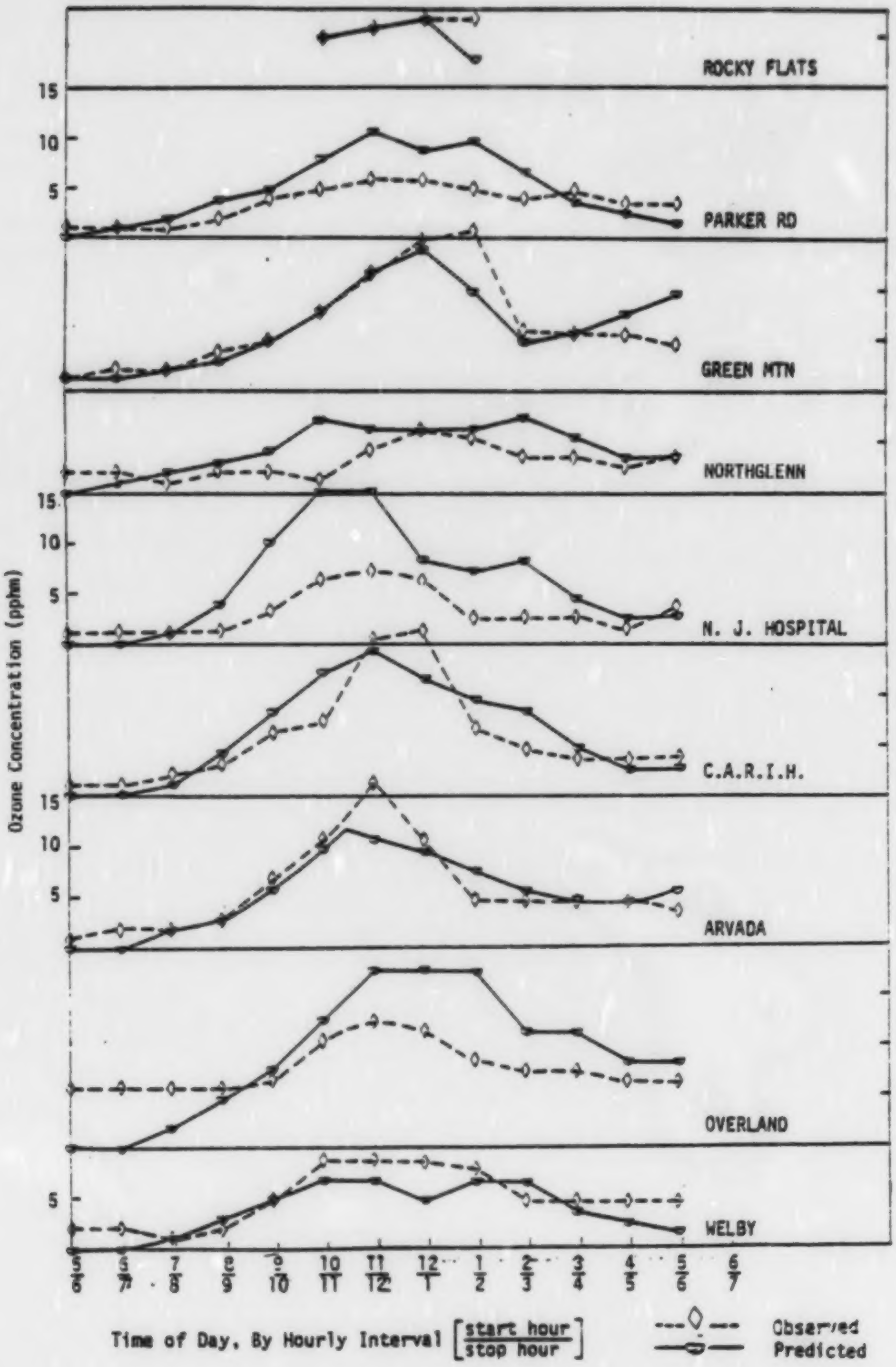
(a) 29 July 1975

FIGURE II-2. OBSERVED AND PREDICTED HOURLY OZONE CONCENTRATIONS (pphm) AT VARIOUS STATIONS



(b) 28 July 1976

FIGURE II-2. (Continued)



(c) 3 August 1976

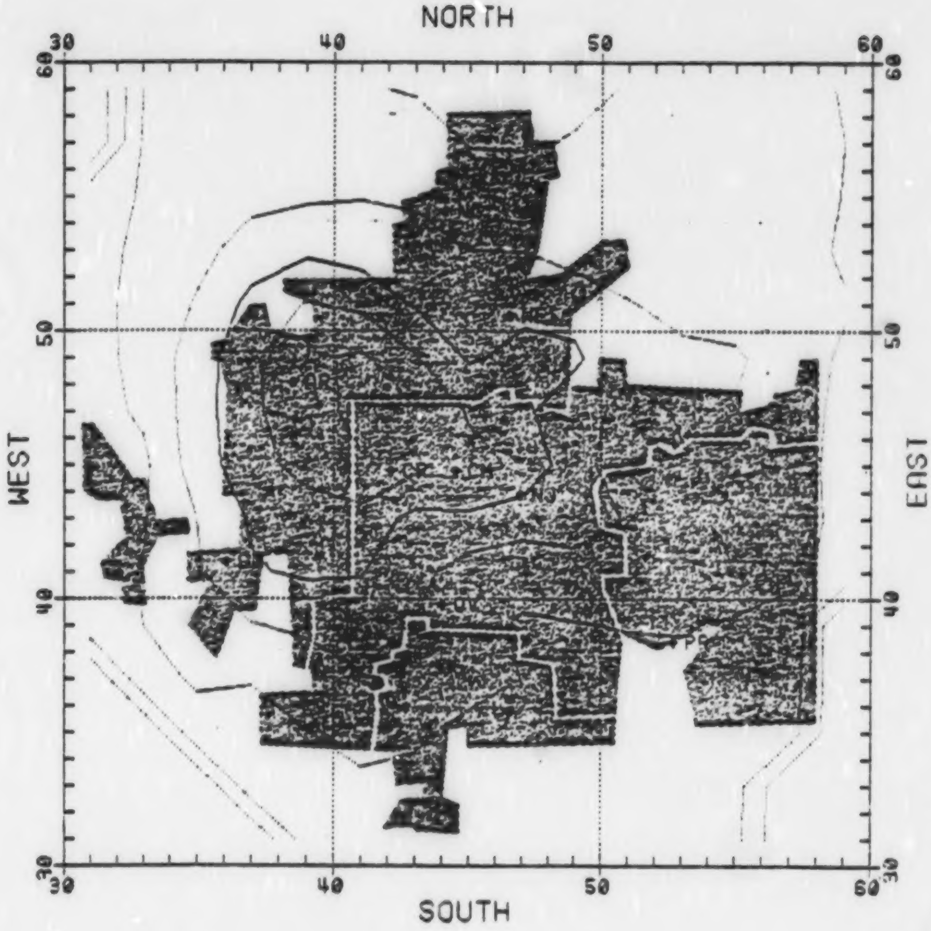
FIGURE II-2. (Concluded)

"pools" in areas protected from ventilation. Thus in the stable early morning atmosphere, particularly strong ozone concentration gradients can be expected, with the highest concentrations expected in protected areas very near the ground. Since the predicted concentrations represent averages over four square miles horizontally and at least 50 feet vertically, it is likely that these values would be quite low, much lower than some possible measurements. At any rate, subsequent ozone peaks will be mainly determined by morning emissions of hydrocarbons and NO_x rather than by morning ozone, which is low enough according to the measurements to be of secondary importance.

The largest differences between model predictions and station observations are noted during peak ozone periods. During high ozone periods, fresh emissions of NO can cause local reductions in ozone concentrations, as discussed in Appendix A. This local effect would be most pronounced at ground level along very heavily traveled thoroughfares. Studies of microscale street canyon effects by Johnson (1974) show that concentrations of auto emitted pollutants can vary quite significantly even from one side of a street to the other.

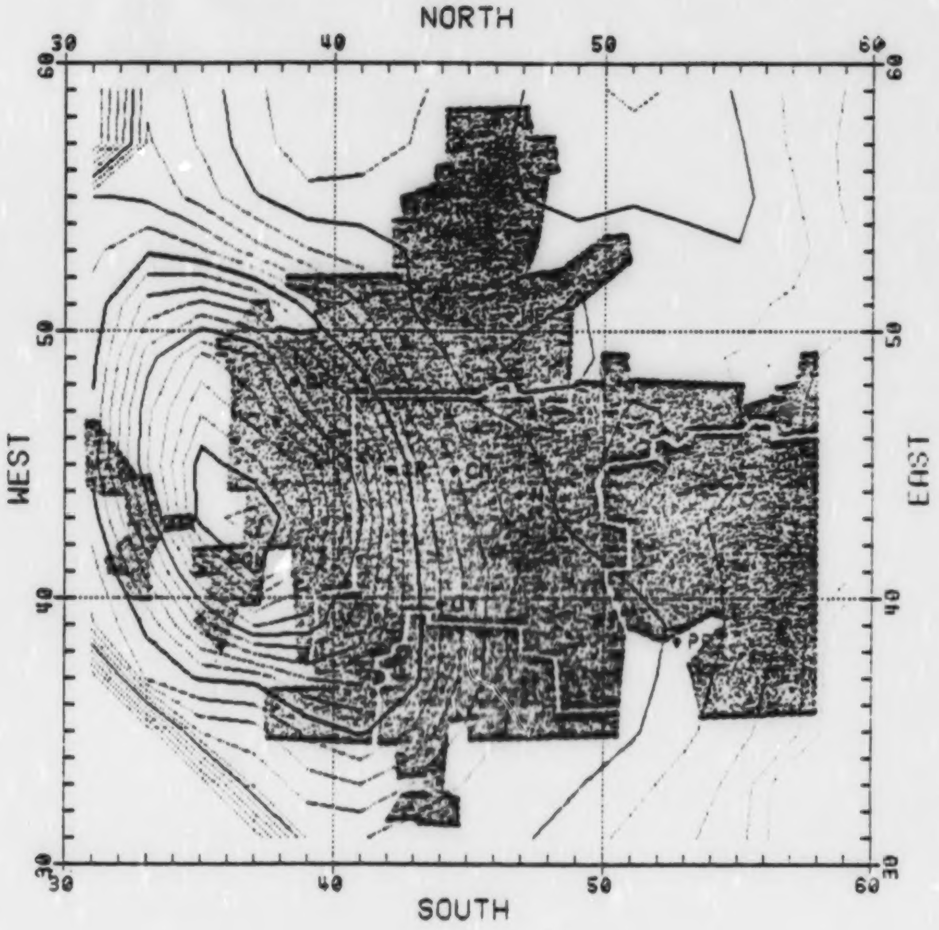
Ozone suppression by NO emissions along heavy traffic routes would cause some monitors to record less than the actual peak values of ozone concentration that might occur very near their location. In Figure II-2(c), for example, ozone peaks predicted for C.A.R.I.H. and National Jewish Hospital on 3 August 1976 are similar, but the observed ozone peaks at the two stations differ by 100 percent. Each of the stations is at the edge of the central business district and might be expected to have similar midday ozone concentrations. The existence of comparable concentrations in the vicinity of both stations is not proved by the simulation but, considering the foregoing discussion, neither is it disproved by the observed values.

The series of two-dimensional isopleth maps of predicted ozone concentrations in Figure II-3 show that on 29 July 1975 a few hours "cooking" of the morning rush hour emissions were required to produce


NORTH
SOUTH
WEST
EAST
30
40
50
60

(a) Hour 0800-0900 MST

FIGURE II-3. ISOPLETHS OF OZONE CONCENTRATIONS (pphm) ON 29 JULY 1975. Isopleth interval 1 pphm.


NORTH
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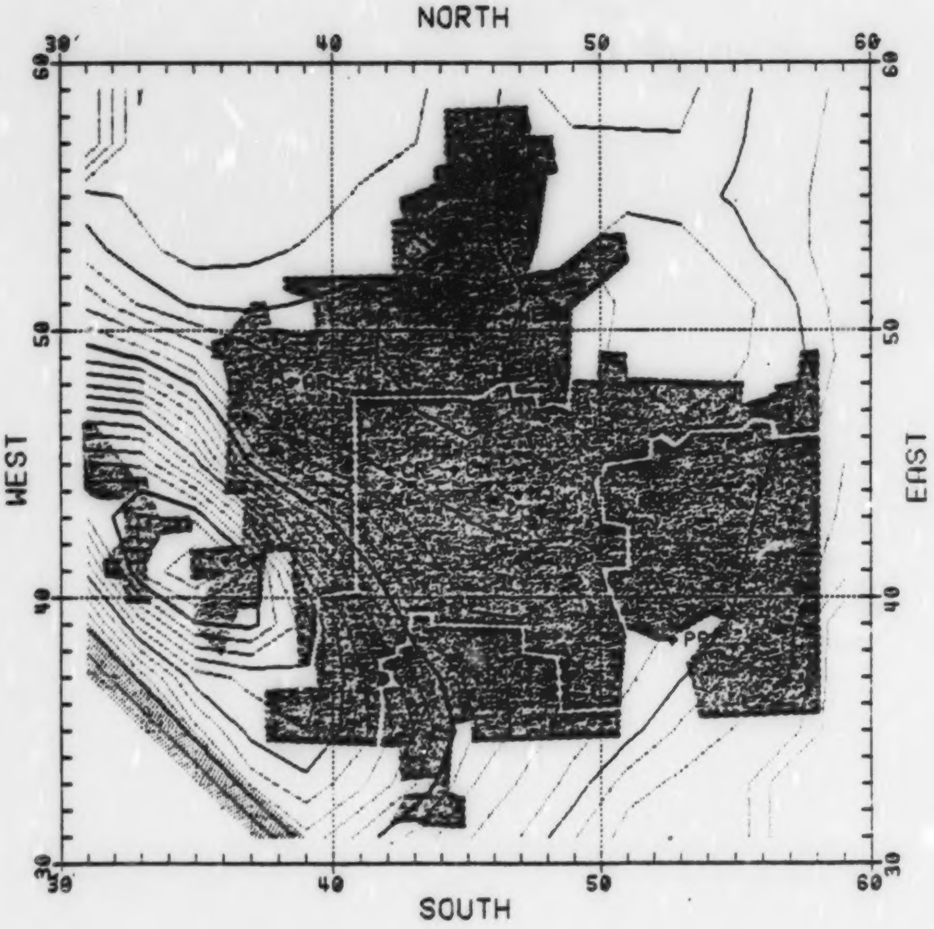
(b) Hour 1000-1100 MST

FIGURE II-3. (Continued)


NORTH
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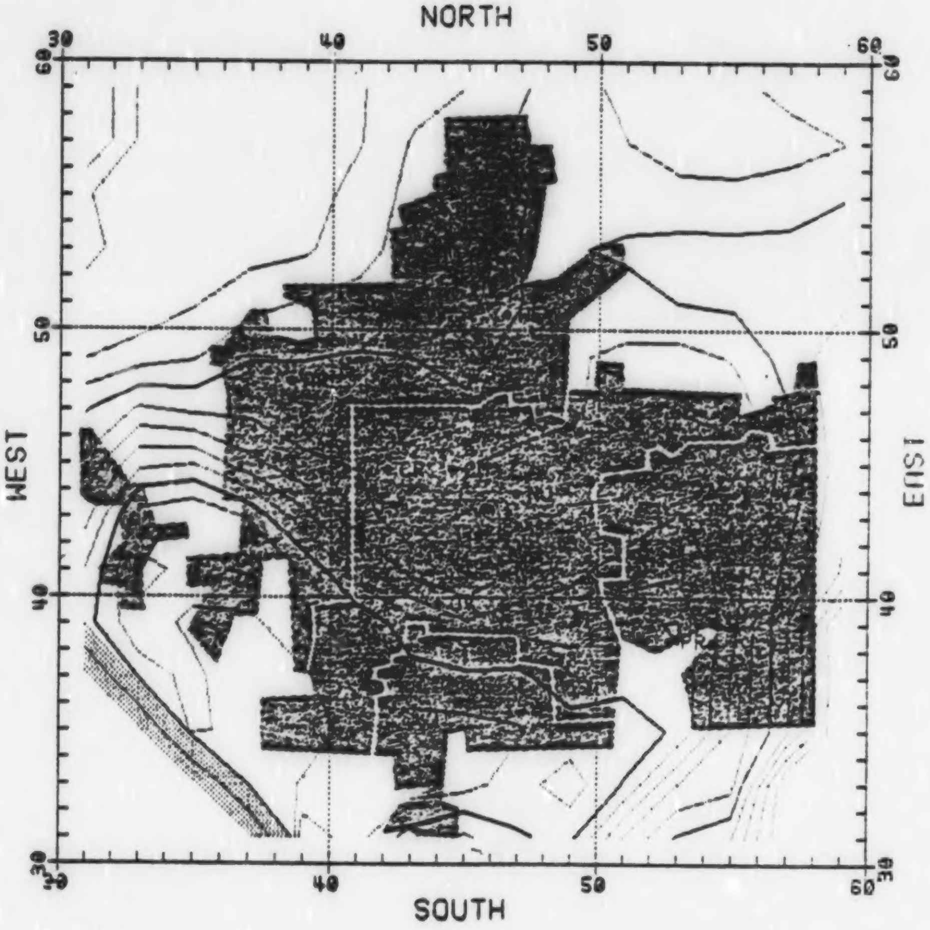
PP

(c) Hour 1200-1300 MST

FIGURE II-3. (Continued)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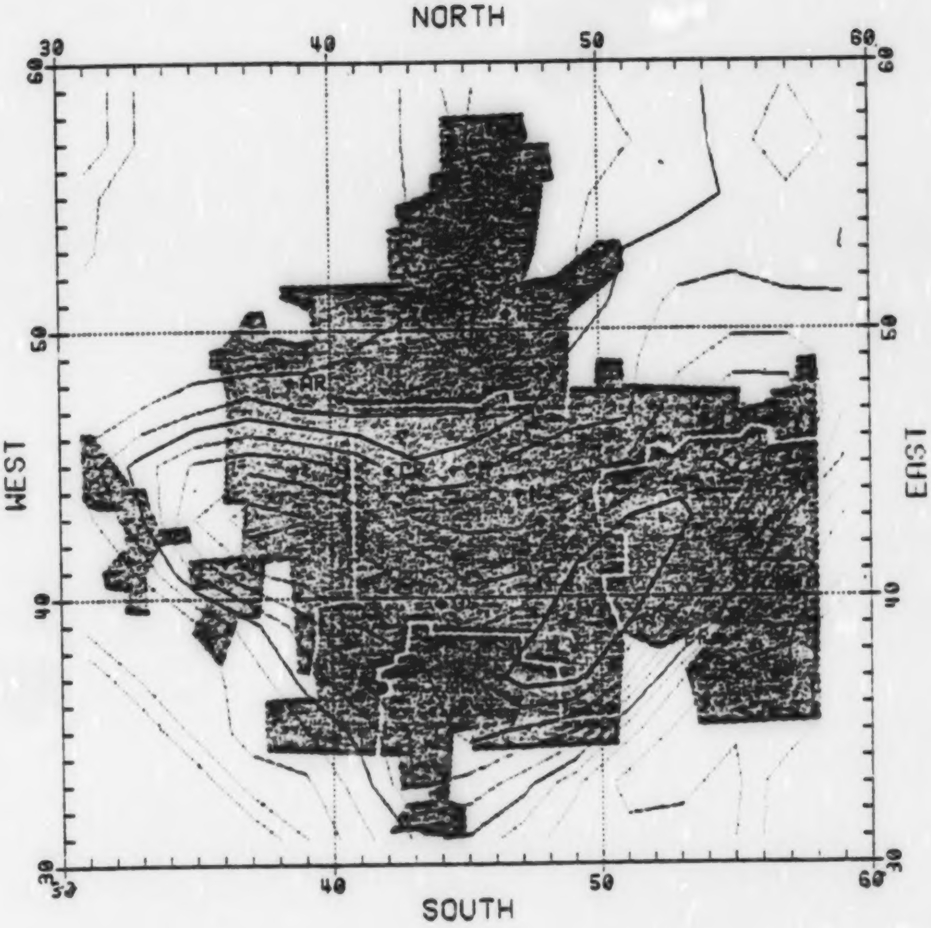
(d) Hour 1400-1500 MST

FIGURE II-3. (Continued)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(e) Hour 1600-1700 MST

FIGURE II-3. (Concluded)

the maximum ozone concentration. (The highest ozone shown here is 23+ pphm at 12 a.m. to 1 p.m.) The ozone "cloud" subsequently drifted to the south edge of the analysis region and then back northeastward across the region. Any portion of the cloud that left the modeling region before this flow reversal would be lost to the simulation.

It appears likely that in the real atmosphere, as in the model simulation, ozone can be swept off the edge of the modeling region. If the winds are such as to bring the material back, the model simulation results will be in error; subsequent ozone concentrations will be underpredicted along the path of the missing ozone. In the three simulation runs, this effect appeared most pronounced on 29 July 1975 and could account for the low afternoon concentration predictions on that day.

2. Analysis of Ozone Comparisons

Several statistics of the observations, the model predictions, and the differences between them have been calculated. They are discussed in the following sections to provide measures of the Denver Model's performance and an understanding of what may be expected of it. In the final section of this chapter, the Denver Model's performance is compared with that of other air quality models.

The comparisons presented earlier (Figure II-2) clearly showed predicted ozone variations during the course of a day that were of the same magnitude and occurred in much the same time patterns as the observed variations. If some part of the differences between predictions and observations are regular then those differences might indicate aspects of the model that could be improved; that is, consistent biases may be indicative of functional shortcomings. To test this possibility, the data were averaged over all stations for each day. These averages are plotted in Figure II-4 along with the data averaged over all three days.

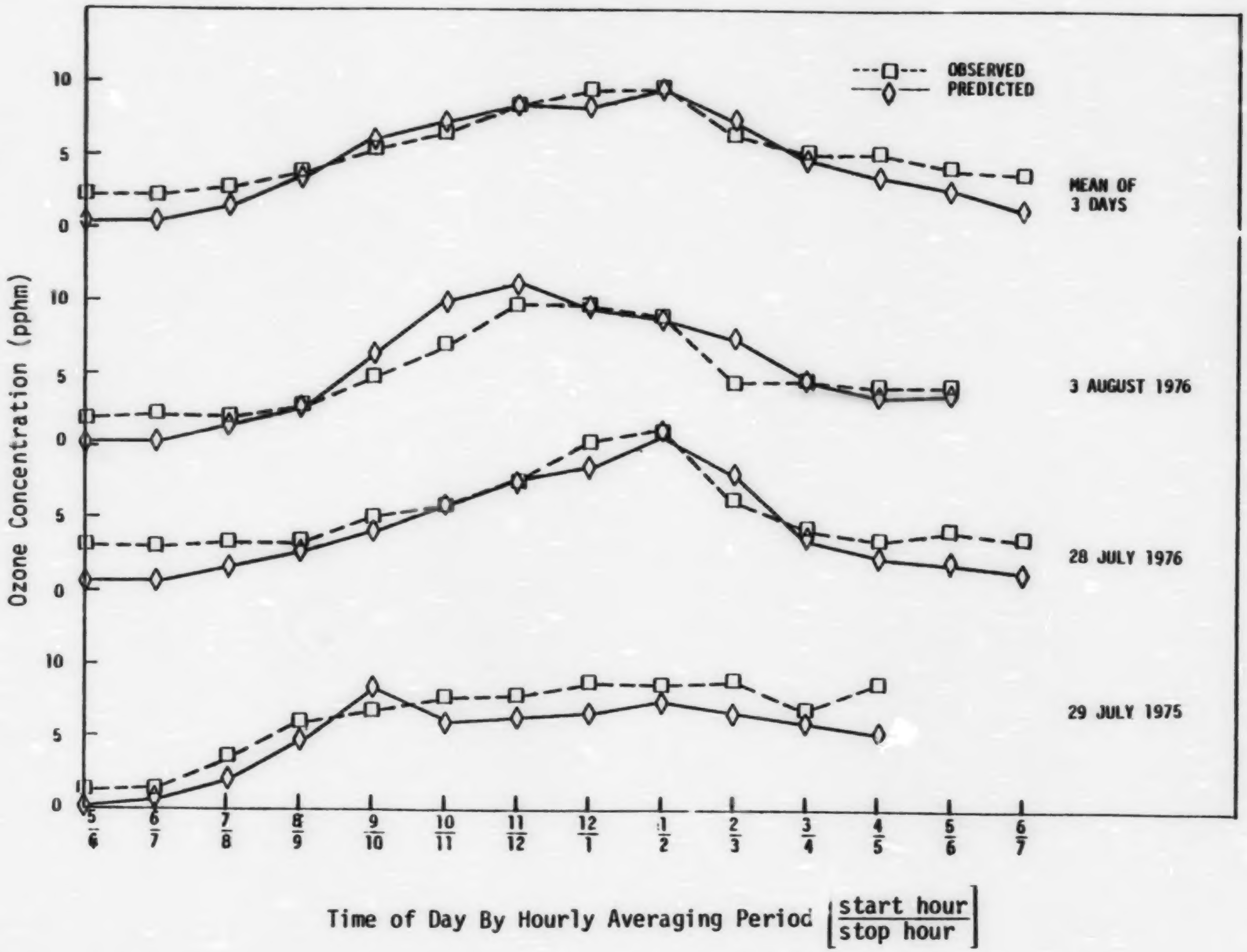


FIGURE II-4. TIME VARIATIONS OVER ALL STATIONS OF OBSERVED AND PREDICTED AVERAGE OZONE CONCENTRATIONS

It can be seen from this figure that the comparison between observation and prediction improves with each averaging process. The correlation of observations and predictions when averaged over all days and stations is indeed quite good. If the data are also averaged over time of day, the average prediction is found to be just 0.4 pphm less than the average observation.

Of course, individual differences are hidden by the averaging process. The absence of any significant differences between averaged observations and predictions shows that the magnitude and phase of the predictions are each quite good. It is particularly notable that the comparisons seem about equally good on each of the three simulation days, although the time variations are rather different on each day. Thus, no basic model shortcomings are identified by this measure.

A more sensitive comparison of these averages is given in Figure II-5. In this figure are shown differences between the pairs of data from Figure II-4. These results seem to show no clear pattern. The variation seems similar on two of the days but even on these days no simple interpretable pattern is apparent. While this lack of pattern certainly does not prove the validity of the Denver Model, it lends no support to any inference of basic model error.

The cumulative frequency distributions of observed and predicted concentration values are presented in Figure II-6. Since the occurrence of concentrations of many pollutants has been observed to be log-normally distributed (Larsen, 1971), the present data were plotted on log-normal scales. It may be seen that although the distributions approach log-normality (a straight line on these scales) at high ozone concentrations, they certainly do not display this property over the whole range of values. The curvature found indicates a more frequent incidence of low ozone concentrations than would be consistent with a log-normal incidence of high ozone concentrations. This finding supports the view that the concentration distribution of ozone is strongly biased by background ozone not related to the complex source distribution or to the random effects of wind

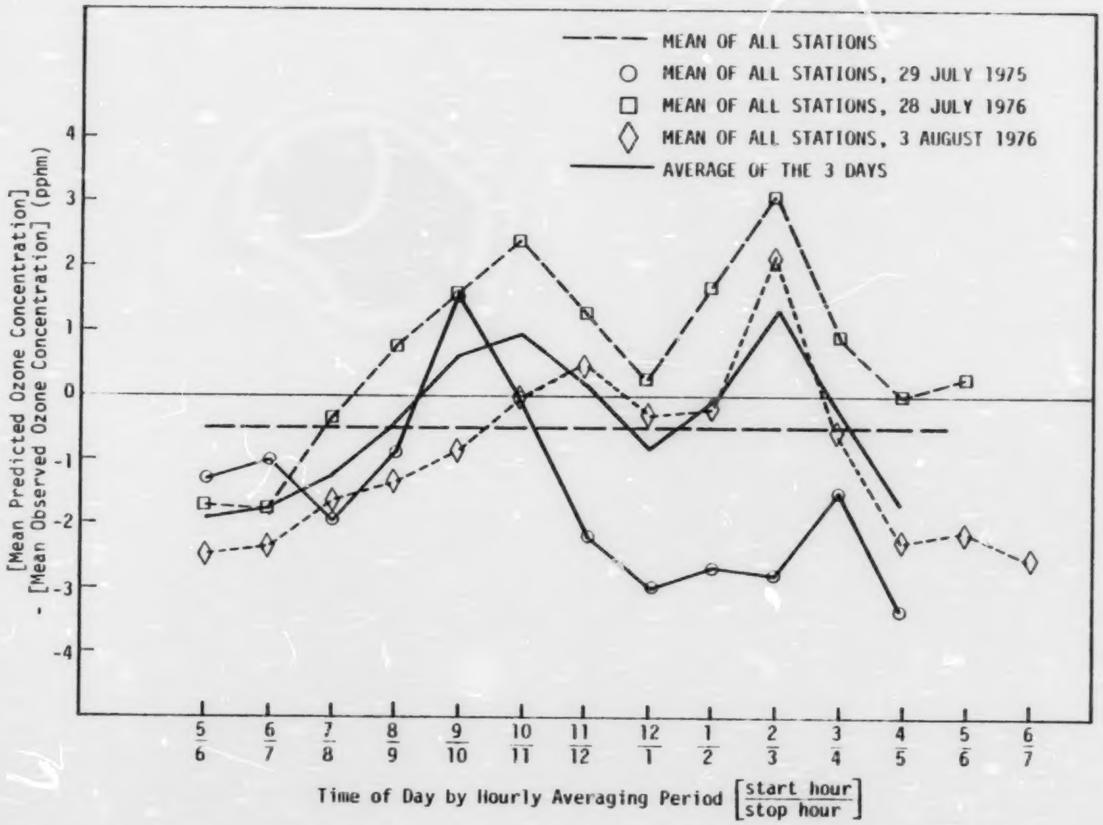


FIGURE II-5. TIME VARIATION OF DIFFERENCES BETWEEN MEANS OF OBSERVED AND PREDICTED OZONE CONCENTRATIONS

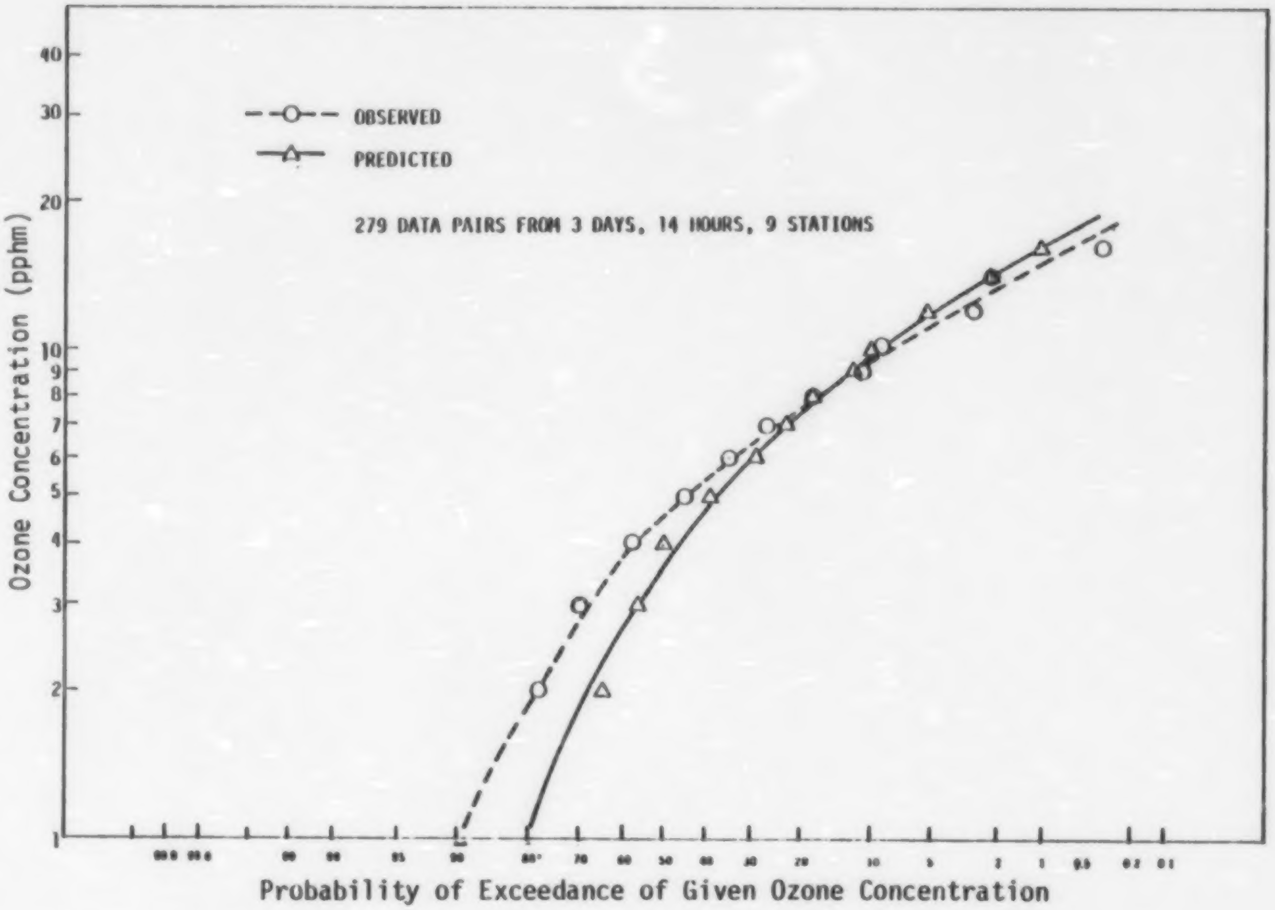


FIGURE II-6. PROBABILITIES OF OZONE CONCENTRATION EXCEEDANCE

speed and direction. Material that has been subjected to dispersive effects for a long period of time becomes nearly uniformly distributed in both space and time.

The probability-of-exceedance distribution for such material approaches a step function: very high probability of exceeding lower than background values, changing to very low probability of exceeding higher values. If log-normally distributed concentrations of material from more random sources are added to background concentrations, the net distribution becomes qualitatively like that shown in Figure II-6. A conclusion that might be drawn from this distribution is that although background concentrations of ozone are not well-determined (low background concentrations are difficult to measure accurately), the higher concentrations are more predictably distributed. The probability appears to be quite high that the Denver Model is capable of reproducing a representative distribution of the higher, and thus more important ozone concentrations.

The correlation between observed and predicted ozone concentrations may be seen in Figure II-7. The numerical correlogram in this figure shows the number of occasions for which any particular combination of observed and predicted concentrations were obtained. Observations and predictions would be perfectly correlated if all points lay on the diagonal through the origin. The points, in fact, lie generally along the diagonal but with a substantial spread about that line.

The mean fractional deviation of points from the diagonal is given in Figure II-8. This plot shows that aside from a small underprediction at the lowest concentrations, the mean fractional deviations are both modest and apparently random. These data do not confirm any finding of systematic error in the simulations.

The distribution of points about the correlation line is presented in Figure II-9. The data curve in this figure is a plot of sums of numbers along diagonal lines in Figure II-7. In this plot the modal

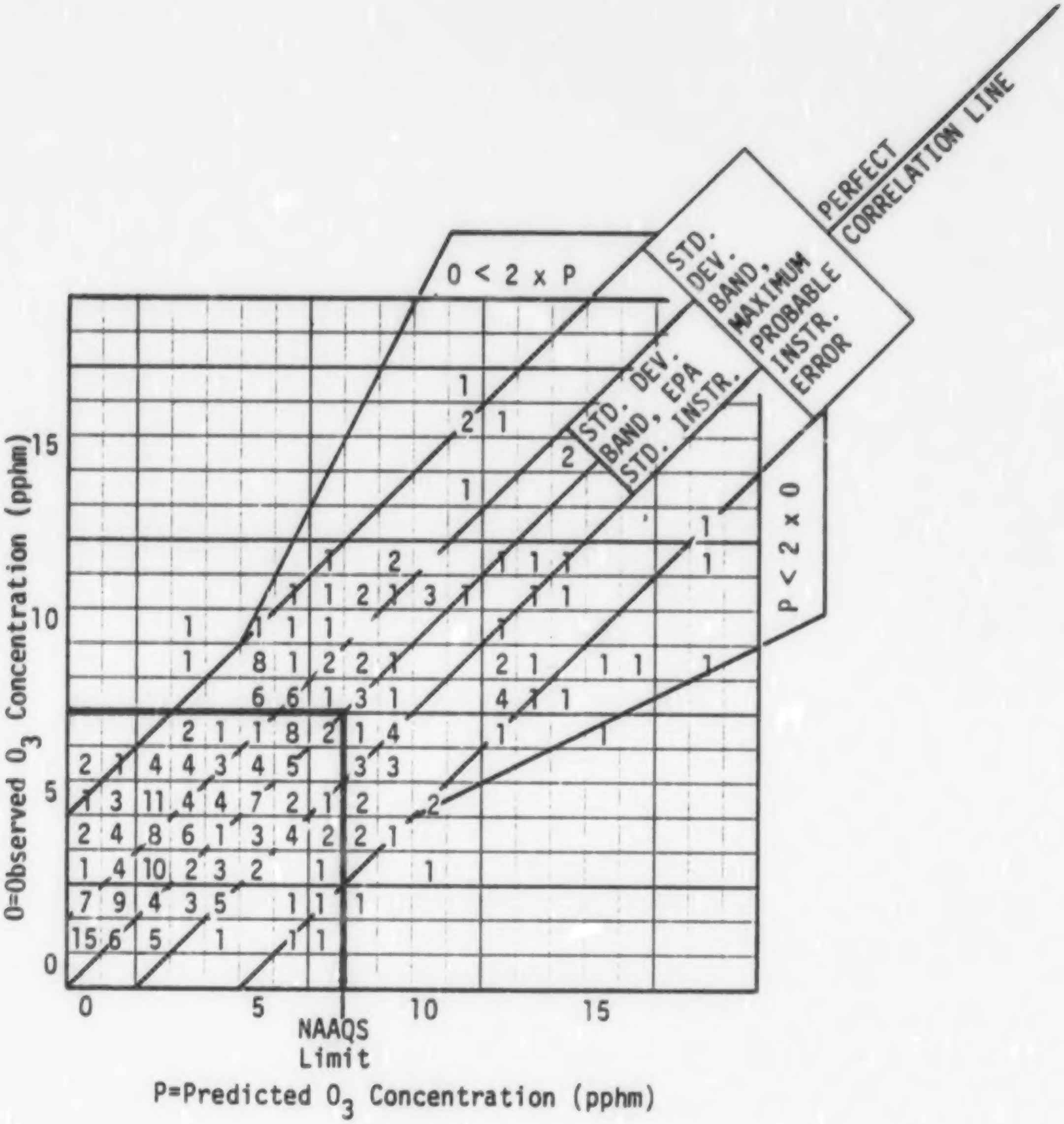


FIGURE II-7. MODEL PREDICTIONS CORRELATED WITH INSTRUMENT OBSERVATIONS OF OZONE (DATA FOR 3 DAYS, 9 STATIONS, DAYLIGHT HOURS)

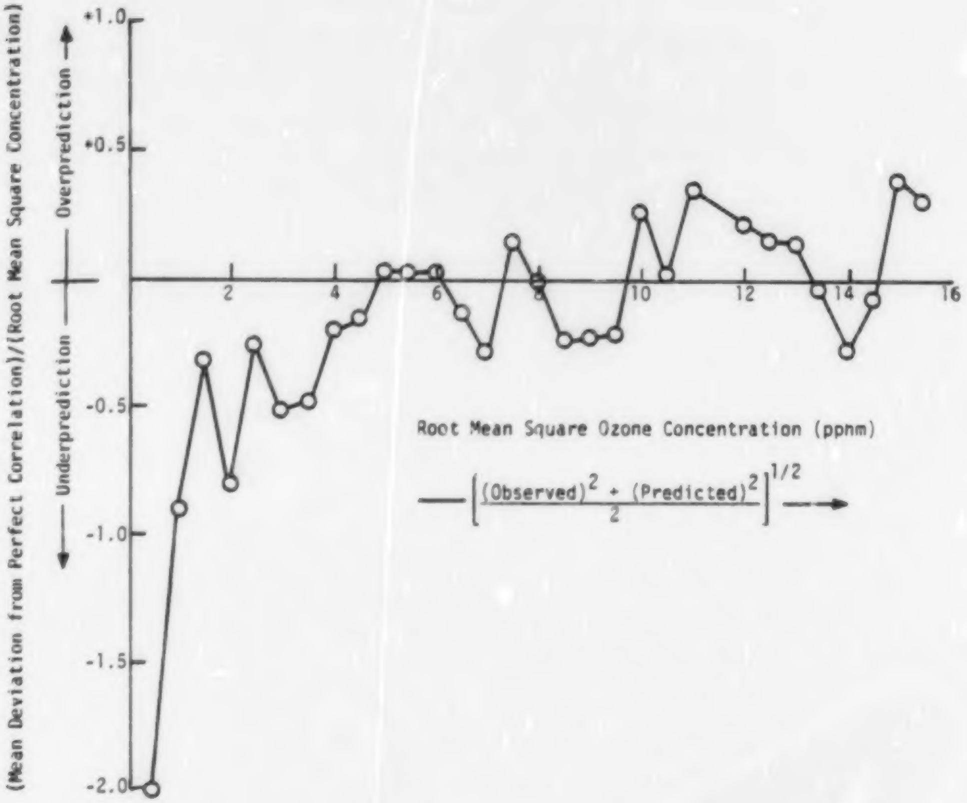


FIGURE II-8. ESTIMATE OF BIAS IN MODEL PREDICTIONS AS A FUNCTION OF OZONE CONCENTRATION

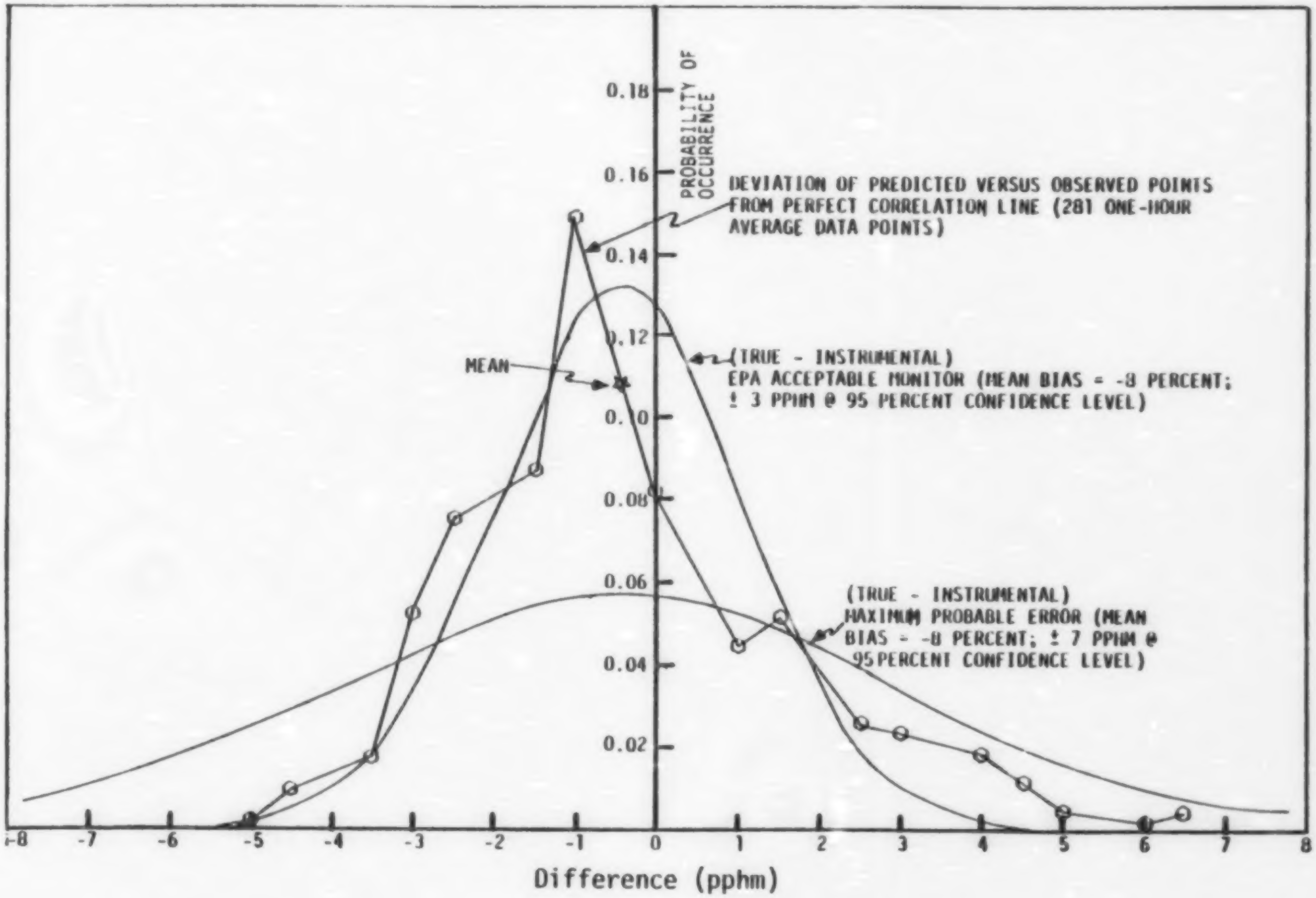


FIGURE II-9. MODEL PREDICTIONS COMPARED WITH ESTIMATES OF INSTRUMENT ERRORS FOR OZONE (DATA FOR 3 DAYS, 9 STATIONS, DAYLIGHT HOURS)

difference between prediction and observation is seen to be approximately -1 pphm. The mean difference is, as noted before, -0.4 pphm. This is ~7 percent of the mean observed value of 5.6 pphm. The distribution is roughly normal, although slightly skewed.

The data distribution in Figure II-9 is not a measure of prediction "error," since the observations cannot be taken as perfect measures of "truth." Burton et al. (1976) present an extensive analysis of ozone monitoring techniques and measurement errors that might be anticipated. Estimates from this analysis have been used to plot the "true-instrumental" normal distribution curves also shown in Figure II-9. The parameters used to define this normal distribution were:

> A bias of -8 percent (-0.4 pphm) because it is estimated that "...The 1% and 2% neutral buffered potassium iodide calibration methods produce results that exceed those by... [absolute reference] methods, probably by a factor of 1.08 ± 0.08..." (Burton et al., 1976, p. I-7).

> A standard deviation of 1.5 pphm for measurements made with an EPA-acceptable monitor because "...for conditions of use where a variety of ozone concentrations are measured, an estimate of the maximum accepted measurement inaccuracy is ± 0.03 ppm..." This value of ± 3 pphm is taken as the 95 percent confidence limit, which is at twice the standard deviation (ibid, p. III-15).

> A standard deviation of 3.5 pphm for measurements made with EPA-accepted monitors because "...the maximum uncertainty that should be attributed to a value assigned to any one-hour-average oxidant/ozone concentration--using any given instrument--in the neighborhood of 0.08 ppm...[at] the 95% confidence limit is...± 0.07 ppm." (ibid, p. III-32).

> An area equal to the area under the predicted-observed data curve.

The sharper normal distribution curve in Figure II-9, which represents estimated performance consistent with EPA acceptance standards [40 C.F.R. §53.30 - §53.32 (1975], appears substantially equivalent to the distribution of prediction/observation differences. These two curves represent different, but related, parameters. The predictions and observations each represent independent estimates of the true concentrations. According to statistical theory, one would expect the error distribution to be independent and, therefore, the distribution of error differences to be the geometric sum of the individual error distributions.

Put another way: we wish to know the expected "error" (i.e., difference from "truth") of the computed predictions. We do not know the true concentrations. The observations are independent, but imprecise, measures of truth. The standard deviation of the difference between the predicted and observed estimates of truth should be the square root of the sum of the squares of the standard deviations of the observational estimates and the predicted estimates. Since the 95 percentile point of the difference distribution is about ± 4.2 pphm and twice its standard deviation is about 2.6 pphm, the difference distribution is clearly not broader than the more optimistic instrument error curve. These observations lead to the following possible alternative explanations:

- > The predicted results add nothing to the error, i.e., the predictions are perfect.
- > The observations are closer to the truth than estimated.
- > The results are fortuitous; more data would show a wider distribution of predicted/observed differences.
- > Some combination of the above situations exists.

It would seem that the first alternative can be rejected out of hand. Even though the difference distribution is no wider than the instrument error distribution, the prediction error cannot be zero.

While the second alternative cannot be rejected, it is highly unlikely to be true since 2 pphm out of the assumed 3 pphm at the 95 percent limit is due to the inherent precision and noise limits of the instrument. Drift and interference errors have to be added to the 2 pphm and they cannot be negligible.

The last two alternatives seem more plausible. A conclusion that may be drawn is that the observational evidence is not precise enough to establish confidence limits for the model predictions, but it is highly unlikely that those limits would be wider than those on the observations; in fact, it is likely that they would be considerably less. Note that if the standard deviations of predicted and observed results (each from the truth) are equal and independent, the standard deviation of the differences should be $\sqrt{2}$ times each individual standard deviation.

An additional conclusion is that differences between predicted and observed concentrations cannot be labeled "errors" and therefore, in Figure II-7, the normal distance of points from the correlation line is a better measure of model performance than the distance along the abscissa (i.e., predicted concentration minus observed concentration).

The parameters of the observational error curves were used to establish the standard deviation bands shown in Figure II-7. There the narrow inner band represents ± the standard deviation of the EPA monitor acceptance standards and the broader band is ± the standard deviation of maximum probable error in EPA accepted instruments in use. Although the standard deviations are probably dependent on ozone concentration level, the actual variation is not well enough known to support presentation here.

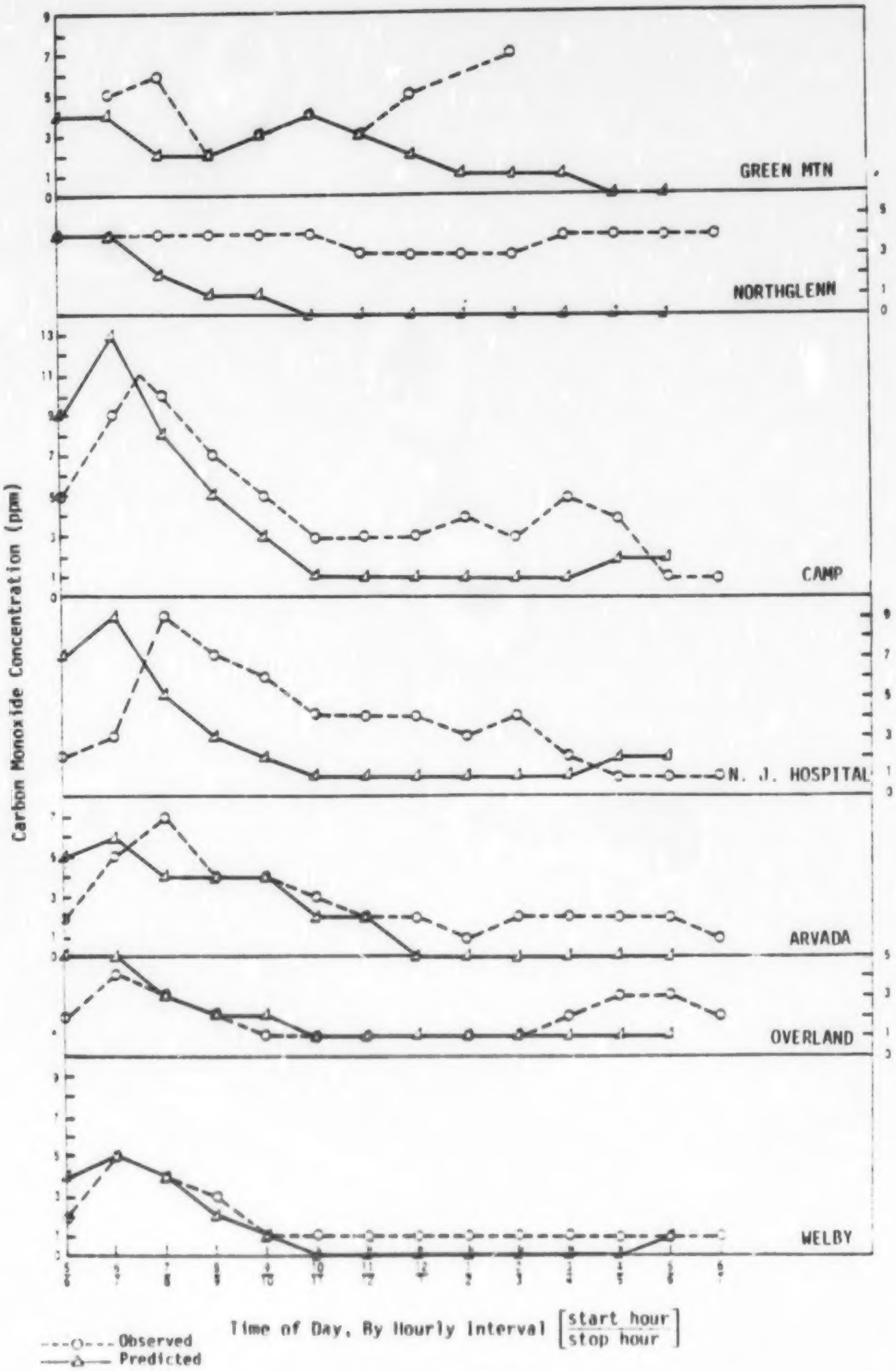
In addition to the standard deviation bands, Figure II-7 shows a sector indicating correspondence within a factor of two. Table II-1 gives further relevant statistics.

TABLE II-1. OCCURRENCE OF CORRESPONDENCE LEVELS OF PREDICTED AND OBSERVED OZONE CONCENTRATIONS

Correspondence Level Between Predicted and Observed Pairs	Percent of Comparisons Meeting Correspondence Level	
	Comparisons	Both Predicted and Observed Conc. > 8 pphm
1) Factor of two (2P > O > P/2)	80%	94%
2) Computed value is within ± twice S.D. max. prob. inst. error (95% level) of observed value	100	100
3) Computed value is within ± S.D. of max. prob. inst. error (95% level) of observed value	93	90
4) Computed value is within ± twice S.D. of inst. errors by EPA std. (95% level) of observed value	89	77
5) Computed value is within ± S.D. of inst. errors by EPA std. (95% level) of observed value	60	37

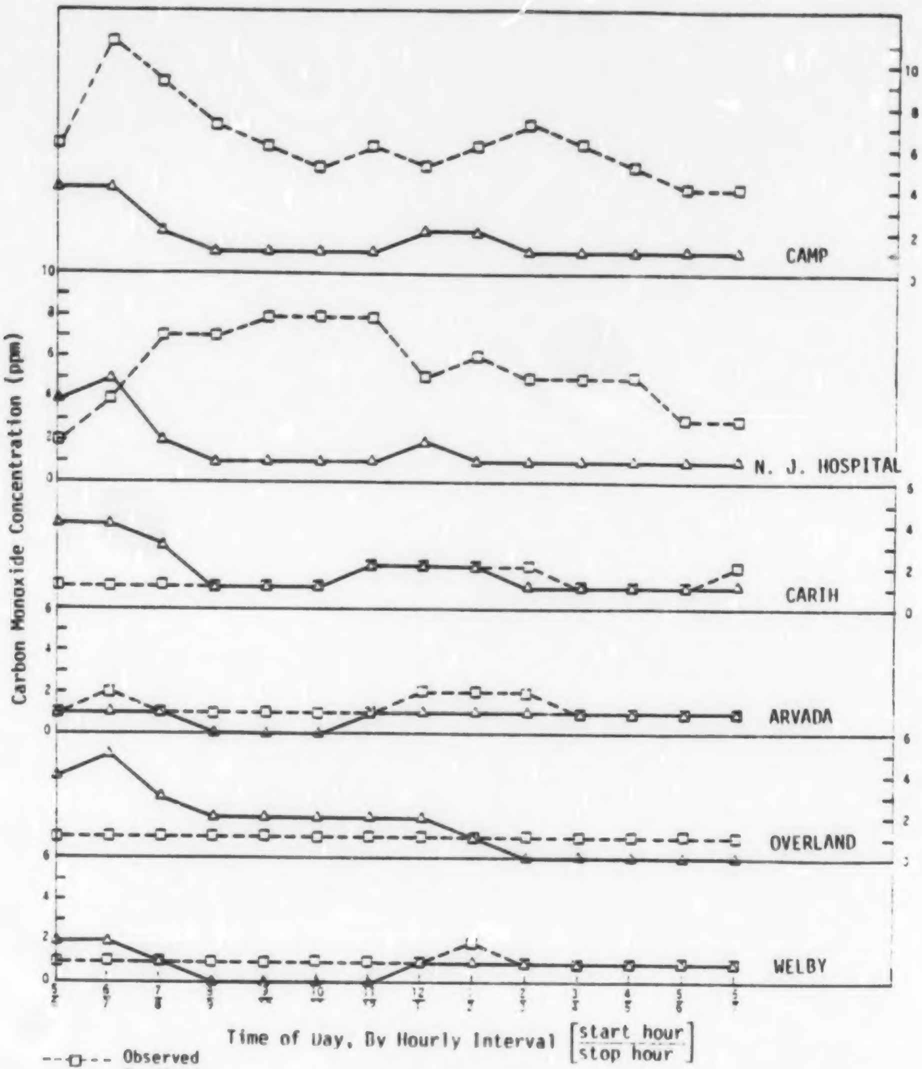
3. Carbon Monoxide Comparisons

Predicted grid-cell CO concentrations are plotted along with station observations in Figure II-10. It shows much more variable correspondence between predicted and observed results than was the case for ozone. In Figure II-10(a), CAMP, Arvada, Overland, and Welby show excellent correspondence for central business district, suburban, and city residential sites. N.J. Hospital, in a heavy traffic inner city zone, shows less good correspondence and Northglenn, a suburban site, shows substantially no correspondence. In the last case, the observed values varied by only 1 ppm during the daylight hours of 29 July 1975. While such measurements could be valid, that possibility seems unlikely enough to at least suggest instrument error.



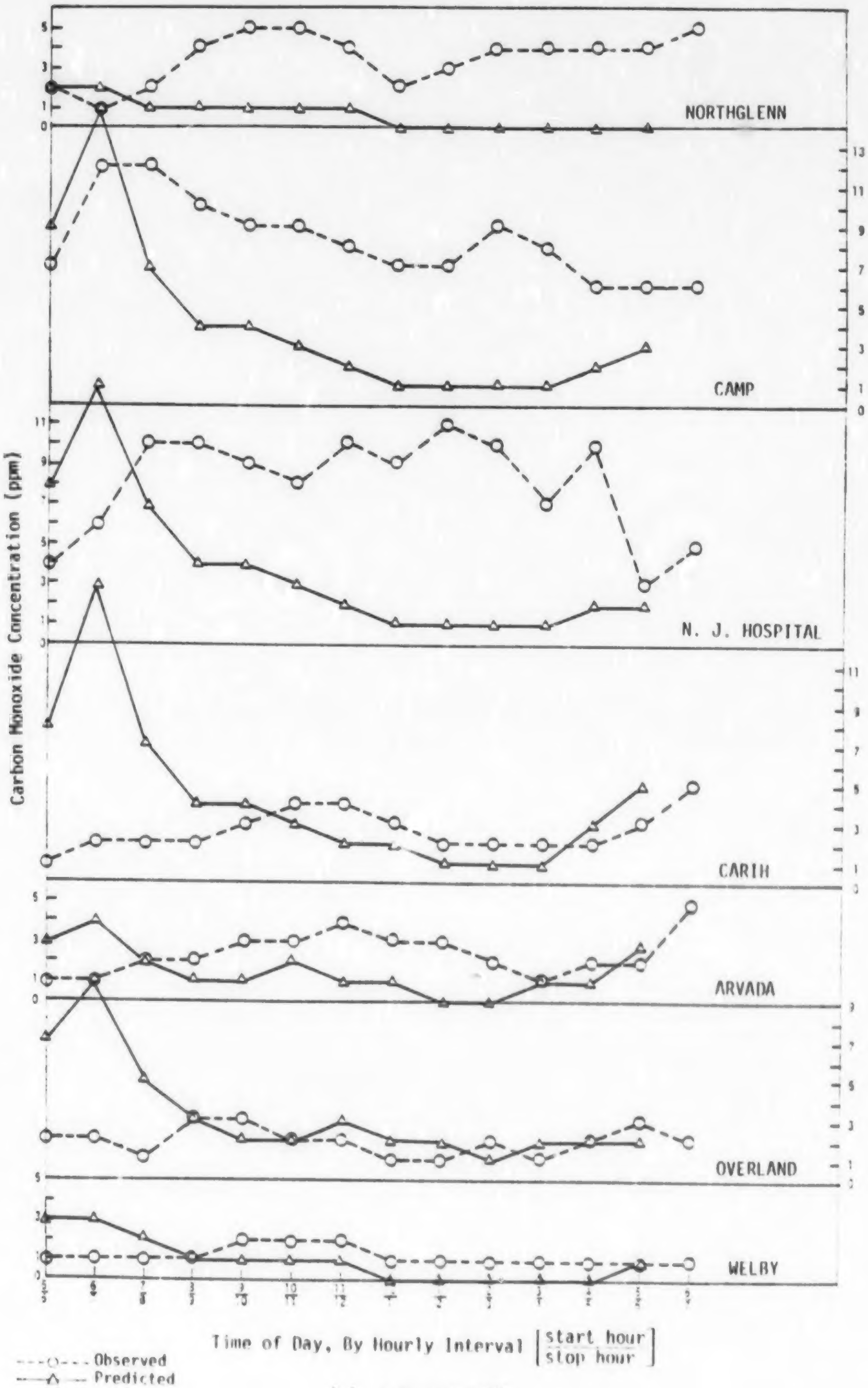
(a) 29 July 1975

FIGURE II-10. OBSERVED AND PREDICTED ONE-HOUR-AVERAGE CO CONCENTRATIONS (ppm)



(b) 28 July 1975

FIGURE II-10. (Continued)



(c) 3 August 1976

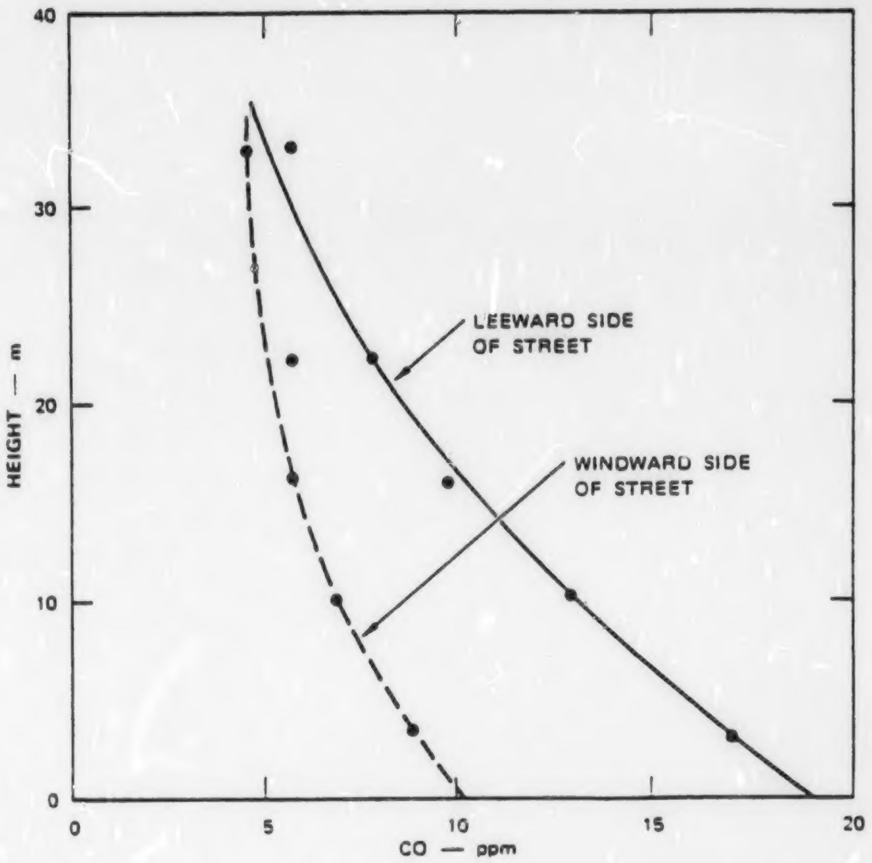
FIGURE II-10. (Concluded)

As Figure II-10(b) illustrates, C.A.R.I.H., Arvada, Overland, and Welby showed observed CO concentrations of 2 ppm or less on the entire day. These concentrations are so low that no meaningful analysis can be made of them. The two inner city sites, CAMP and N.J. Hospital, showed substantial observed values of CO that have very little correlation with the predicted values. Figure II-10(c) also shows both good and poor comparisons with observed concentrations.

The more variable correspondence of predicted and observed CO concentrations, as compared to ozone, is not unexpected. Although CO and the ozone precursors HC and NO_x have much the same source distribution, ozone is not produced until substantial atmospheric mixing has occurred. Ozone peaks in well-mixed clouds while CO concentrations decrease continuously as the material moves away from the vehicle exhaust pipe. Thus, CO concentrations tend to be quite variable on a scale comparable to that by which streets and traffic lanes may be measured. This scale is exceedingly small compared with the size of grid cells in a model simulating photochemical effects.

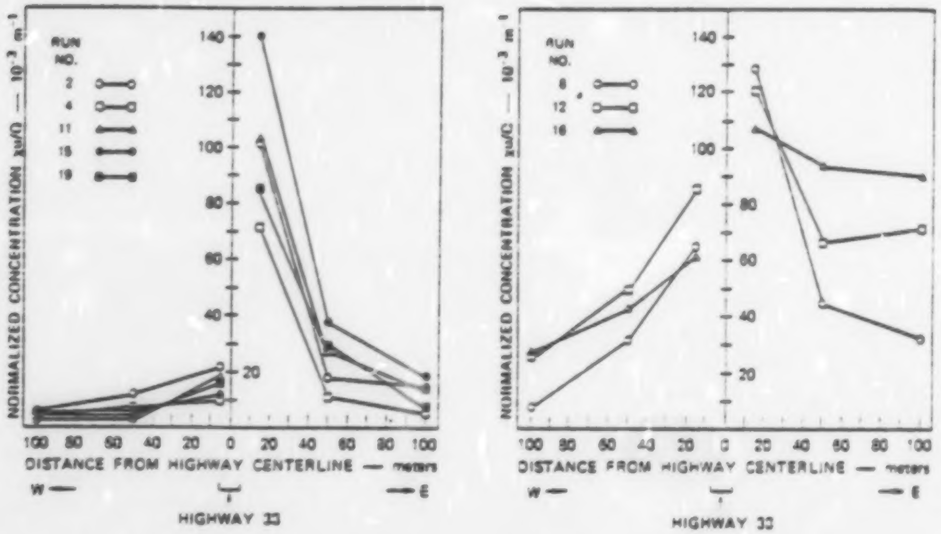
Estimates of local variability of CO concentrations near urban streets have been presented by Ludwig and Kealoha (1975). Figure II-11, reprinted by them from Georgii et al. (1967), shows that surface CO concentrations in an urban street canyon may typically differ by 100 percent from one side of the street to the other. Figure II-12, reprinted from Johnson (1974), shows even greater side-to-side differences (up to ten-to-one ratios) from dye tracer experiments; these results should be representative of nonreactive pollutants.

Ludwig and Kealoha (1975, pp. 83ff) present empirical expressions indicating that the side-to-side CO ratio in a street canyon should be approximately equal to the ratio of the street width to the offset distance of the monitoring instrument from the street. From Eqs. (8a) and (8b) of this reference, we can write



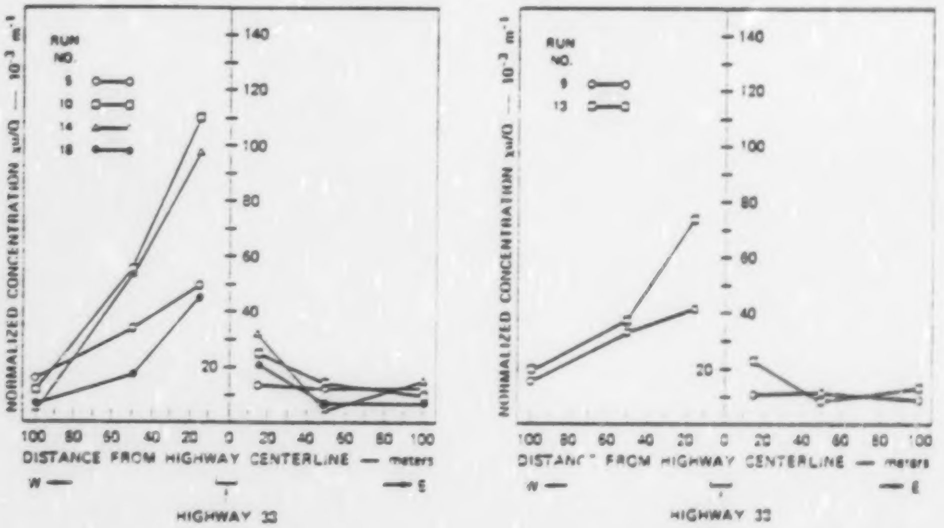
Source: Georgii et al. (1967).

FIGURE II-11. THE VERTICAL DISTRIBUTION OF CO CONCENTRATION IN A STREET CANYON WITH TRAFFIC VOLUME OF 1500 VEHICLES PER HOUR



(a) Distributions for runs with cross-roadway winds from the west (note plotting error--points at 5 m west should be at 15 m west)

(b) Distributions for runs with very light winds from the southwest



(c) Distributions for runs with winds from the southeast sector

(d) Distributions for runs with very light winds from the east

Source: Johnson (1974).

FIGURE II-12. MEASURED TRACER CONCENTRATION DISTRIBUTIONS

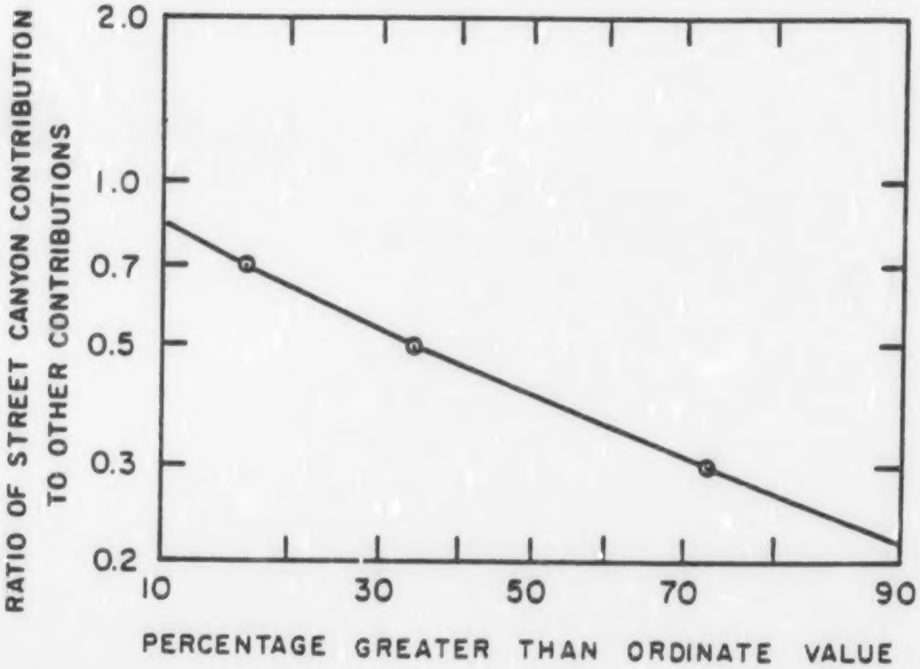
$$\frac{C\ d.w.}{C\ u.w.} = \frac{\sqrt{2 + x^2 + z^2}}{W}$$

where C d.w. is concentration on downwind side (due to street canyon sources), C u.w. is concentration on upwind side (due to street canyon sources), x is horizontal distance from receptor to nearest lane of traffic, z is elevation of receptor, and W is street width. Figure II-13 (reprinted from Ludwig and Kealoha's Figure 29) shows that even an eight-hour-average CO concentration at a point in a city may have one-half of its value contributed by sources within a few meters (i.e., within the street canyon under observation).

An inference that may be drawn from the CO data presented in Figure II-9 is that correspondence between observations and predictions on some occasions is not fortuitous--this should be the case when monitors are not strongly affected by microscale meteorology--but that such correspondence should not be expected on all occasions. Thus the Denver Model may do as well at predicting CO as ozone on a grid-cell-average basis, but instruments are less capable of confirming the CO predictions. Since no adequate measure of true grid-scale CO concentrations is available, model performance with ozone is probably the best measure of model performance with CO.

4. Nitrogen Oxide Comparisons

Comparisons of observed and predicted NO are presented in Figure II-14, and of NO_2 in Figure II-15. Obviously the available observational data were totally inadequate for validation of the Denver Model for these species. NO was never high enough at Parker Road for the instruments to register dependably. This was also true for NO_2 at Green Mountain on 28 July 1976.



Source: Ludwig and Kealoha (1975).

FIGURE II-13. FREQUENCY DISTRIBUTION OF THE RATIOS OF STREET CONTRIBUTIONS TO CITYWIDE CONTRIBUTIONS FOR THE HIGHEST 8-HOUR-AVERAGE CO CONCENTRATIONS

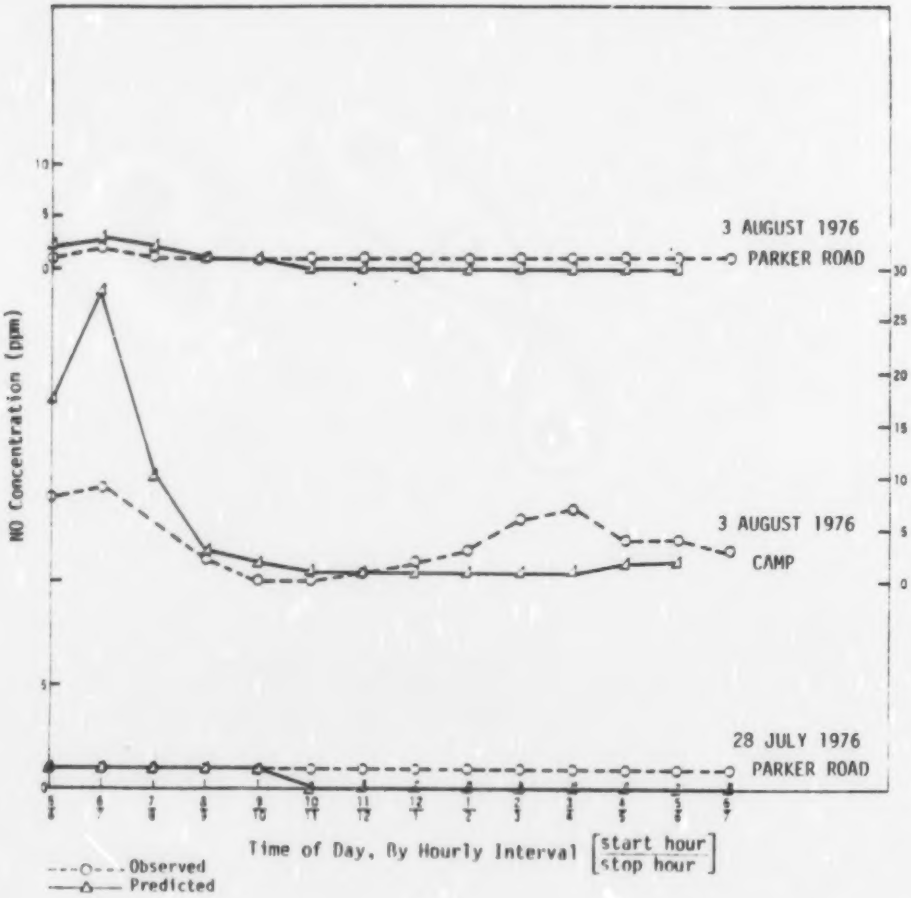


FIGURE II-14. OBSERVED AND PREDICTED ONE-HOUR-AVERAGE NO CONCENTRATIONS

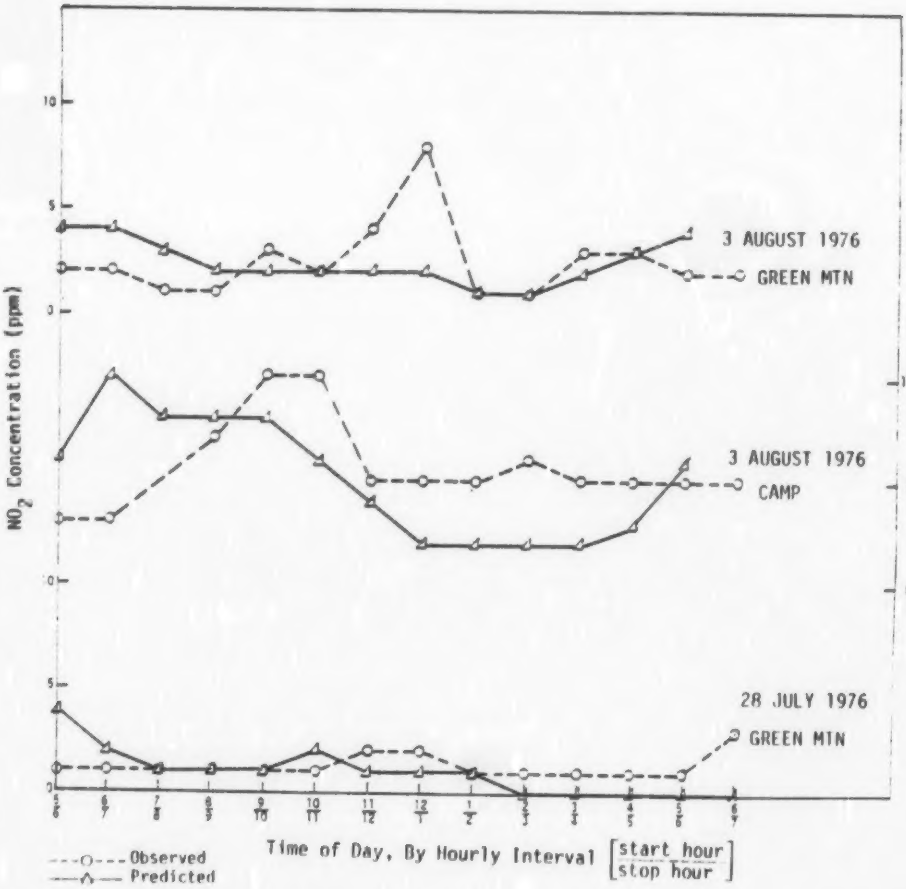


FIGURE II-15. OBSERVED AND PREDICTED ONE-HOUR-AVERAGE NO$_2$ CONCENTRATIONS

NO is susceptible to the same microscale meteorological effects described above for CO. In addition, predicted concentrations of NO, NO_2, and ozone are consistent with each other by accepted chemical principles; that is, the rapid reactions between these species ensure that they are near equilibrium. Observed concentrations of these species, however, are often inconsistent; that is, they are in a local equilibrium which may be quite far from equilibrium at the grid scale. Thus we conclude that validation should rest on the strongest evidence (ozone) and that internal consistency of the model is more defensible than external consistency with data which are not self-consistent.

D. COMPARISON OF THE DENVER MODEL WITH OTHER MODELS

Validation studies of other models in various stages of development have been examined extensively by Roth et al. (1976) and will not be examined here. No photochemical model has been recommended by EPA, however, EPA does recommend the use of rollback [40 C.F.R. §51.14(c)(4)(1975)] for ozone control strategies. EPA is currently considering the recommendation of alternatives in this context. Therefore, it will be informative to contrast some performance measures for models recommended for use by EPA with performance measures of the Denver Model.

The "Appendix J" rollback technique for assessing photochemical oxidant control strategies has not been verified. It does not seem to be subject to verification since verification would involve the trial of an oxidant control strategy for an urban region. Years would be required before an "observation" would be available to compare with a "prediction" and the process would involve changes that might invalidate the prediction. Roth et al. (1976) point out that:

> In a critique of the Appendix J relationship, Dimitriades (1975, p. 9) cited the following strengths of this approach:

> - The graphical relationship is based on actual atmospheric data.
> - The hydrocarbon-oxidant dependence qualitatively agrees with smog chamber data....
> - The relationship can be improved through the acquisition of additional data.
>
> Furthermore, the required calculations are relatively simple and can be carried out graphically, in contrast to more sophisticated relationships...whose governing equation(s) must be solved using a digital computer.
>
> Despite the advantages cited above, the Appendix J relationship has been criticized for a number of reasons. In particular, the following shortcomings have been identified:
>
> - The relationship has not been validated.
> - The effects of NO_x emissions changes are not explicitly treated.
> - The relationship is based on a limited amount of historical air quality data. The accuracy of the lower and upper portions of the curve is limited because of experimental errors and the scarcity of data points, respectively.
> - The influence of local meteorological and emissions patterns is not considered.
> - The data base upon which the curve is based relies on measurements of precursor and oxidant levels taken at the same station.
> - Background concentration levels are assumed to be negligible.

Each of the shortcomings listed above has particular relevance to Denver, but the most important in terms of predicting Denver's future air quality is the second. It is well known (Dimitriades, 1972, 1973, 1975; Merz et al., 1972; Trijonis, 1972; Paskind and Kinosian,1974; Bailey, 1975) that ozone production depends as strongly on NO_x as it does on hydrocarbons.

The nature of this dependence is shown in Figure II-16. The ozone concentrations plotted there were computed using the chemistry portion of the Denver Model. The simulations were of smog chamber experiments and thus do not represent conditions in a real urban atmosphere. The computations assume no wind, constant sunlight, and only initial charges of the precursors HC and NO_x (i.e., no continuous emissions and no background ozone).

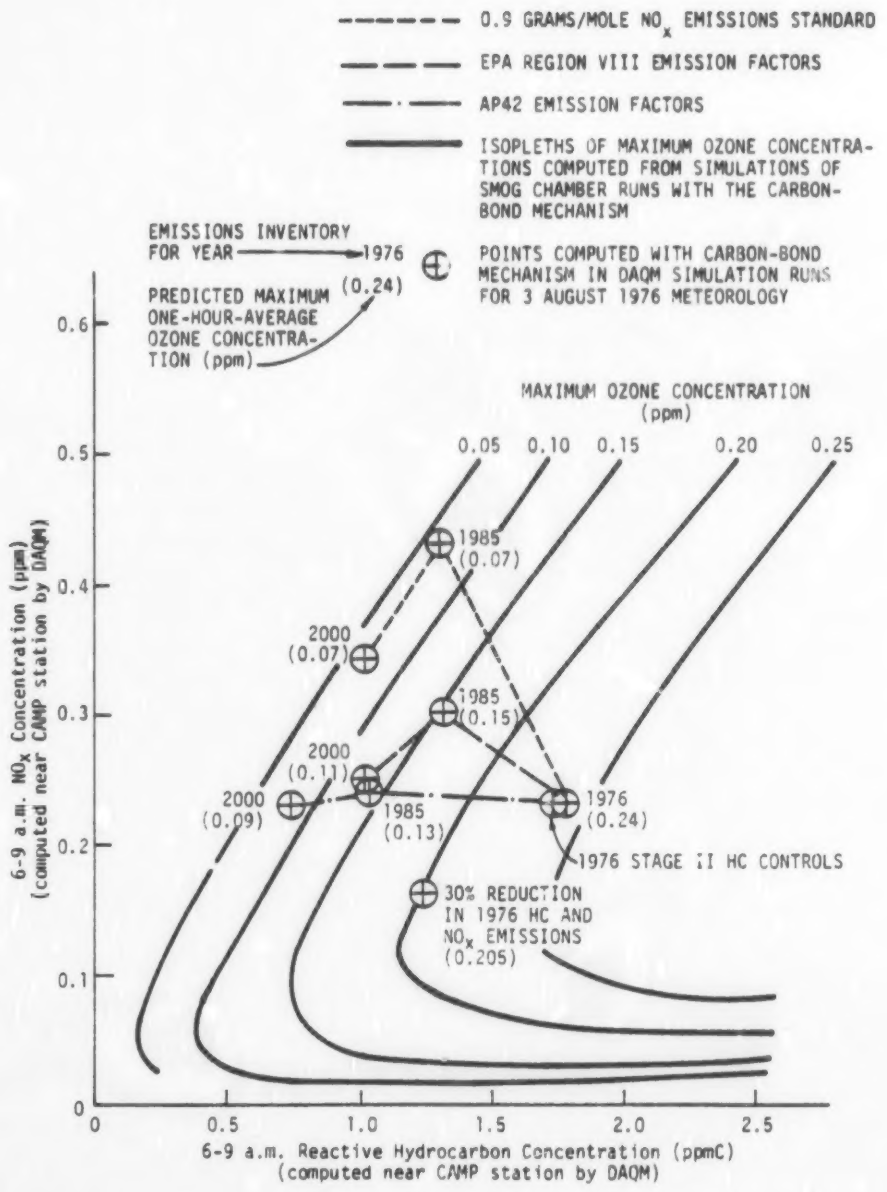


FIGURE II-16. MAXIMUM OZONE COMPUTED BY CARBON-BOND SIMULATIONS OF SMOG CHAMBER EXPERIMENTS AND BY DENVER MODEL FOR VARIOUS ASSUMED FUTURE EMISSIONS

In spite of any nonrepresentativeness of such ozone isopleths, the Denver Model simulation results are plotted in this figure. The 1976 Denver point was determined by the predicted 6 a.m. to 9 a.m. HC and NO_x averaged at N.J. Hospital and at the downtown CAMP station. Points for other years were determined similarly. To account for the different conditions between the simulations used to derive the isopleths and the model's point computation, the isopleths were scaled to give exact correspondence to the 1976 point.

It will be seen that all other points correspond very well also. The high NO_x points for the years 1985 and 2000 represent a relaxation of NO_x emission factor requirements from 0.4 grams per mile to 0.9 grams per mile. The number next to each point is the maximum ozone concentration for the year indicated as computed by DAQM. The low and high NO_x assumptions give quite different ozone predictions but rollback would have predicted identical values. Note that the isopleths do not constitute a prediction system since computed NO_x and HC are required to locate points. It is not practical to use ozone observations to locate points since the maximum predicted ozone concentration was almost 50 percent greater than any observed value. Use of the isopleths as an ozone prediction method would give a 33 percent reduction (in this example) in ozone predictions.

EPA does recommend (even requires) the use of grid-based advection dispersion models for the analysis of SO_2 effects on air quality. Two of these, AQDM and CDM are provided to any interested user by EPA. In addition, EPA (Turner et al., 1973) has done work on comparing the performance of these models with "box" models (regional-averaged dilution models). Turner's analysis compared the performance of the models for SO_2 in New York City on annual average predictions.

Even though the SAI Denver Model was used to generate one-hour concentrations, we list in Table II-2 its performance measures along with information from (Turner et al., 1973) on AQDM, CDM, and two box models

TABLE II-2. VALIDATION MEASURES OF VARIOUS MODELS

[differences = (predicted-observed)/observed]

	Number of Comparisons	RMS Difference	Mean Absolute Difference	Lower Limit Difference	Upper Limit Difference	Difference Range
SO_2 Annual Averages*						
AQDM	75	0.90	0.68	0.64	2.30	2.94
CDM	75	0.39	0.27	0.87	1.23	2.10
Gifford (box)	75	0.61	0.53	1.30	0.22	1.52
Hanna (box)	75	2.44	1.32	1.07	9.13	10.20
Mean	75	1.08	0.70	0.97	3.22	4.19
O_3 Hourly Averages						
SAI Denver Model	279	0.31	0.35	0.90	1.16	2.06

---

* SO_2 model measures were computed from data in Turner et al. (1973).

(Gifford's and Hanna's). This table shows that the Denver Model validation measures are based on many more data points than are the SO_2 validations (the Denver Model has one point per simulation hour at each station, the others achieve the performance they do by averaging a year's data into each comparison). Nevertheless the Denver Model displays more favorable performance by almost every measure.

E. CONCLUSIONS

Conclusions that may be drawn from this validation study are as follows:

> The Denver Model is a very good predictor of one-hour-average ozone concentrations in grid cells in the Denver region.

> The model's ozone predictions at any given station probably have at least as narrow an error distribution as do measurements at the same station.

> If predicted and observed concentration estimates are equally accurate, Denver Model predictions can be expected to be within a factor of $\sqrt{2}$ of true concentrations 80 percent of the time, and its predictions of exceedances (i.e., more than 8 pphm) could be expected to be within that factor 94 percent of the time.

> The accuracy of predictions by the Denver Model of regional maximum ozone concentrations should exceed the accuracy of predictions of concentrations at specific stations.

> The Denver Model is likely to underpredict ozone concentrations when ozone and/or precursor concentrations initially or on an inflow boundary are unknown but higher than expected.

> The model predicted maximum ozone concentrations that are nearly 50 percent higher than any observed in the 1976 summer study, yet predictions for grid squares containing monitoring stations are consistent with observations at monitoring stations. It could thus be expected that observations up to 50 percent higher than in the 1976 study could be made without justifying any inference of worse air quality.

III BASE CASE STUDIES

The major goal of this project was to predict the effect of the proposed wastewater treatment facilities on future air quality in Denver. The most important way that the treatment plants would have an effect on air quality in Denver is by supporting the increase in pollutant emissions associated with urban growth and development.

Since urban growth and development and the attendant increase of pollutant emissions depend on factors in addition to the availability of sewage systems, and, in particular, since urban development depends on decisions not yet made, predictions of future growth are not simulations of reality in the sense that physico-chemical models are. To analyze Denver's future air quality then becomes an exercise in hypothesis. The question is not so much "What will Denver's air quality be?" but rather, "What will Denver's air quality be if ...?" Such a question inevitably evokes the question "What will Denver's air quality be if not ...?" Thus there is no single, unique analysis of future air quality. The variation of air quality with changes in hypotheses is an important aspect of the analysis, but to define the changes there must be an initial, neutral, or "base" state from which to measure departure.

The base state of Denver's air quality for the future years under study, 1985 and 2000, is taken to be a state that would possibly be realized if growth patterns are not affected by the results of this analysis. Since plans and projections for Denver's future have been formulated, examined, and accepted in the absence of this analysis, those plans became the "base" of the base case. The most questionable aspect of the base case definition is the assumption that vehicle emissions will be as described in EPA document AP-42 (Supplement 5). Recent work by the staffs of EPA Region VIII and Colorado APCD led to the conclusion that emissions will be much higher than AP-42 values unless very strict control measures are instituted (see discussion in Chapter V).

The generation and features of future plans for Denver are given in detail in Appendix C. Data files necessary to carry out the base case simulations were provided by Colorado Division of Highways and the Air Pollution Control Division of the Colorado Department of Health. Descriptions of these files are given in Appendix B.

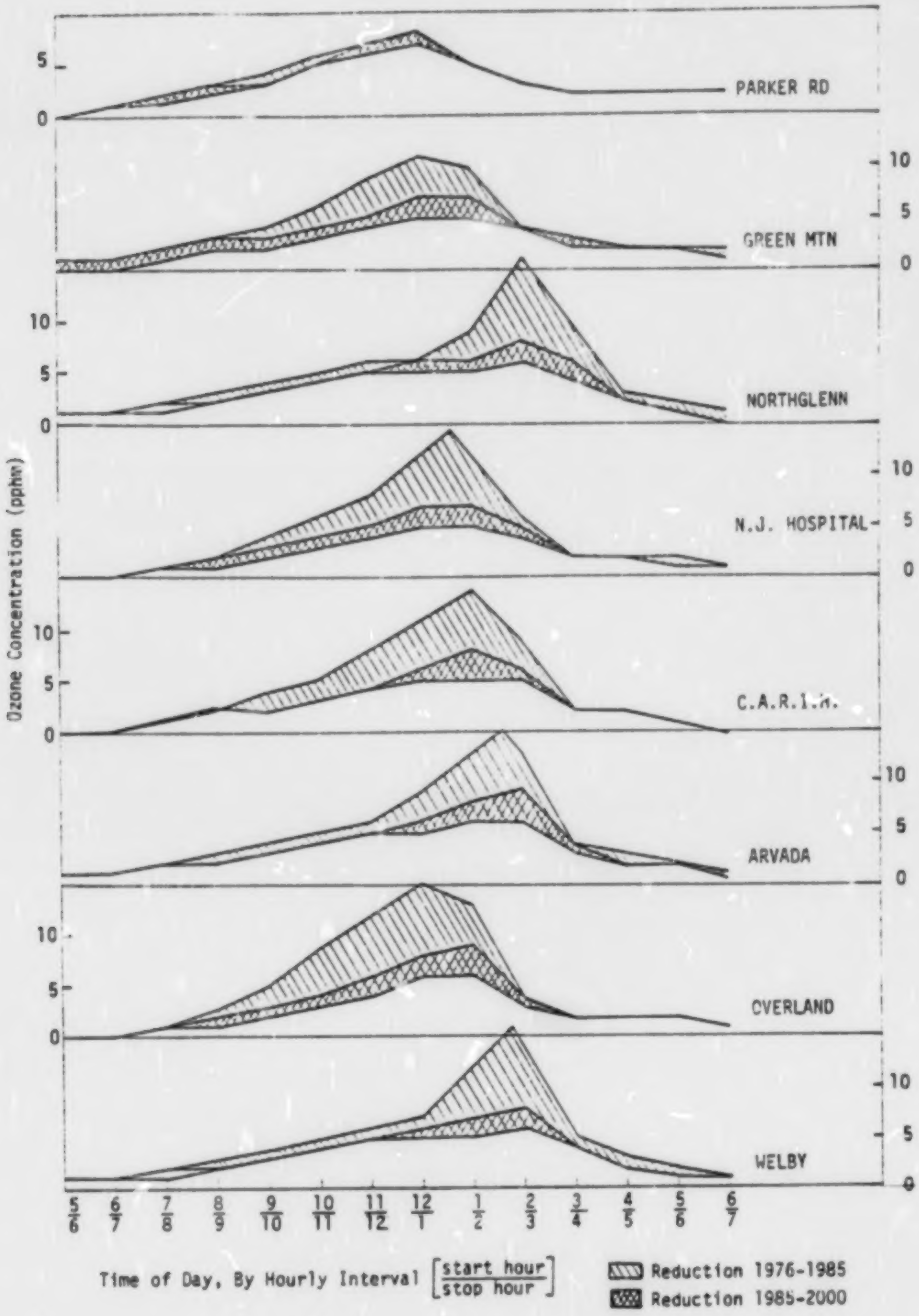
Air quality, on any given day, depends on detailed wind and turbulence patterns as well as on emissions. Since these patterns cannot be predicted, even in the sense that emissions can, it is necessary to define representative meteorology. For the base case studies, the meteorology for the two summer 1976 days that were selected for validation was used. Similarly the CDM simulations of annual average conditions used the same STAR meteorological data as were used for 1976 simulations. Since the 1976 summer days chosen led to estimated worst-case ozone concentrations, their meteorological conditions can be expected to be representative of the worst conditions in the future years also.

A. BASE CASE OZONE CONCENTRATIONS PREDICTED BY THE DENVER MODEL

1. Station Comparisons

Ozone concentrations predicted by the Denver Model for grid squares containing monitoring stations are plotted for each base case year in Figure III-1. The area between successive concentration traces is shaded, with hatching between 1976 and 1985 and cross-hatching between 1985 and 2000.

The basic nonlinear character of the photochemical oxidant problem is clear. Even though the wind and turbulence patterns are identical, the 1985 concentrations are not a constant fraction of the 1976 concentrations. The ratio of those concentrations varies with time at a given station and varies from station to station at a given time. The differences in concentration with a constant wind pattern occur because with different emissions a parcel of air arrives over each pollutant source area with different species concentrations, and thus the parcel has a unique set of reactions along its trajectory for each year studied.



(a) Meteorology for 28 July 1976 Assumed

FIGURE III-1. REDUCTION IN PREDICTED OZONE CONCENTRATIONS (pphm) AT DENVER STATIONS DUE TO PREDICTED FUTURE EMISSIONS CHANGES

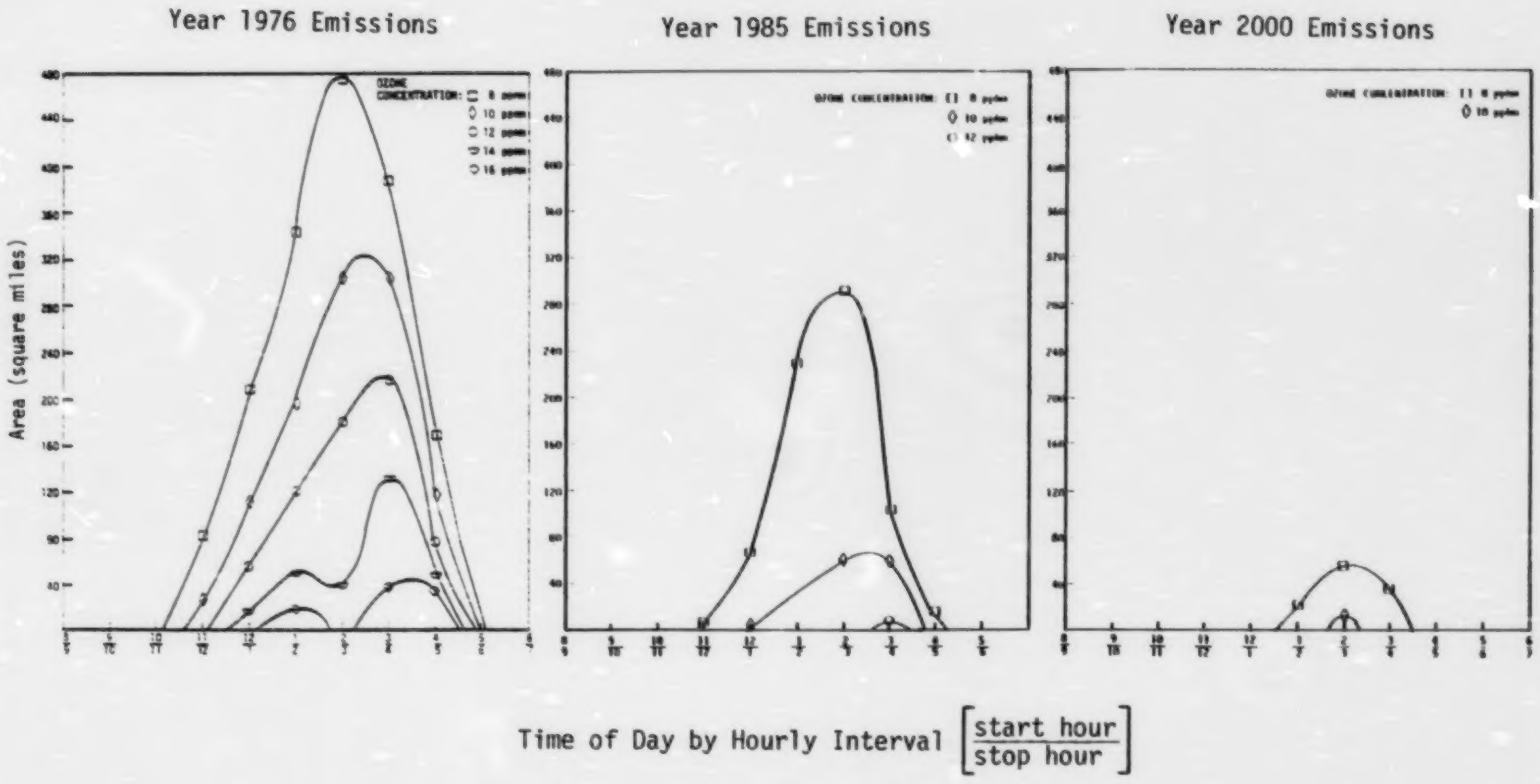
In general, the absolute and fractional reductions are greater in the 1976 to 1985 period than in the 1985 to 2000 period. Peak reductions in the earlier period average 44 percent. Peak reductions in the latter period only average 23 percent. Absolute reductions of the peaks are much more substantial than are reductions of lower concentrations. As noted above, the peak predicted concentrations at measurement stations are closer to the peak observed concentrations than to the absolute peak concentrations, which are predicted for locations other than measurement stations. In the base case runs for 1976, the peak predicted ozone concentration at any station was 16 pphm on 28 July 1976, the same as the observed peak. The peak predicted anywhere was 22 pphm. On 3 August 1976 the station peak predicted was 15 pphm; observed was 17 pphm. The concentration predicted anywhere was 24 pphm.

Because of the nonlinearity of the photochemical process, there is no assurance that a station might not experience an absolute peak on some future day, but the ratio of the peak concentration predicted at a station to the peak predicted anywhere is 0.77 in 1985. This is about the same as the 1976 value of 0.70. In 2000 the ratio is higher (0.85), but it is still significantly different from 1.0. The peak predicted ozone concentrations at stations are 10 pphm in 1985 and 6 pphm in 2000.

2. Area Comparisons

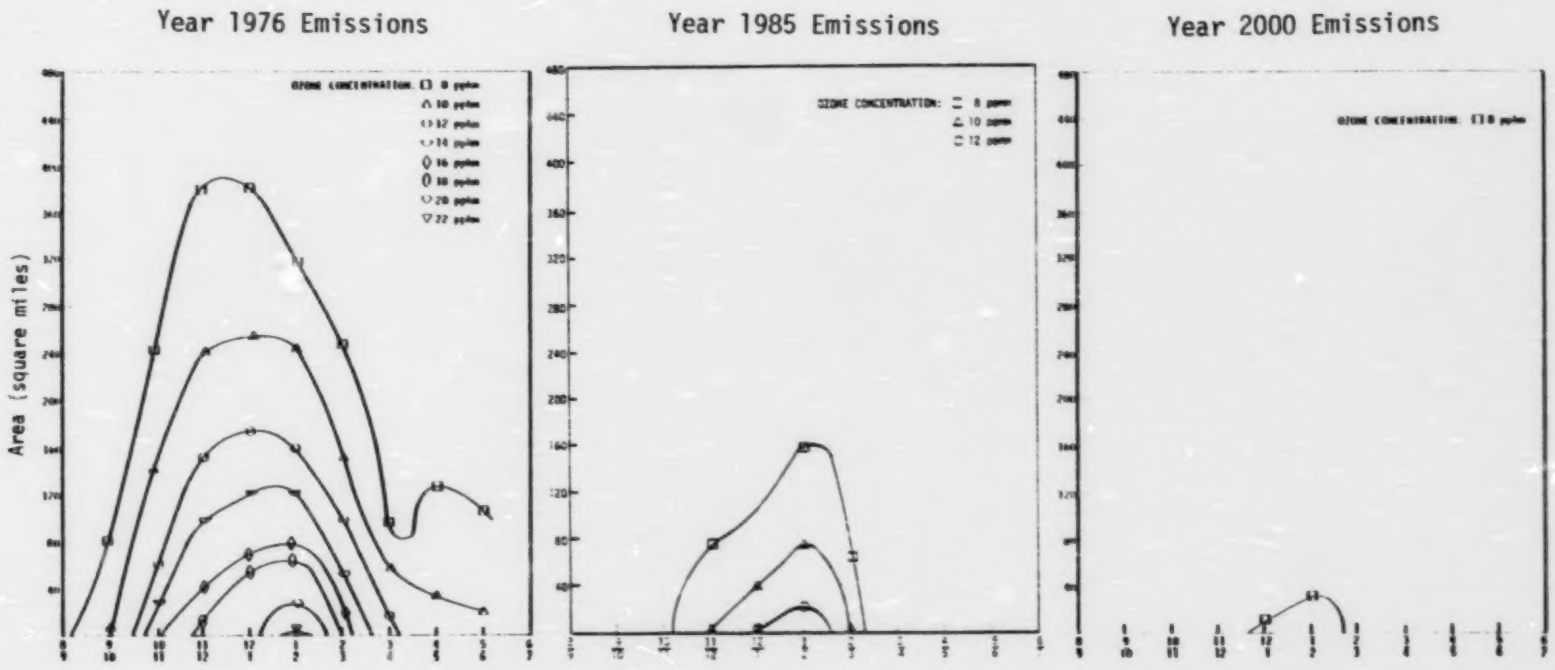
Measures of the peak predicted ozone concentrations and the areal extent of several levels of NAAQS exceedances are presented in Figure III-2. In this figure, the area in which a given exceedance of the ozone NAAQS is predicted is plotted as a function of time of day. Exceedance levels plotted are 0 pphm (i.e., standard just met, no violation), and even numbers of pphm above the standard.

In 1976 the NAAQS for ozone is first reached between 9 and 11 a.m. each day. About one-half of the region experiences ozone concentrations at the NAAQS or higher at a peak hour between 12 and 2 p.m. The area of exceedance is greatly reduced or eliminated by late afternoon.



(a) Meteorology for 28 July 1976 Assumed

FIGURE III-2. SIZE OF AREA IN WHICH PREDICTED OZONE CONCENTRATIONS EQUAL OR EXCEED GIVEN VALUES FOR YEARS 1976, 1985, AND 2000



Time of Day by Hourly Interval $\left[\frac{\text{start hour}}{\text{stop hour}}\right]$

(b) Meteorology for 3 August 1976 Assumed

FIGURE III-2. (Concluded)

In 1985, not only is the peak predicted ozone concentration much reduced from the 1976 level, but the area affected by 8 pphm ozone is reduced by 40 to 60 percent and the area affected by 10 pphm ozone is reduced by 70 to 75 percent. The area affected by 12 pphm is nearly eliminated.

By 2000 predicted areas of exceedance are only about 1.5 percent of the modeling region, and are predicted to occur for only a single one-hour averaging period.

B. BASE CASE CARBON MONOXIDE CONCENTRATIONS PREDICTED BY THE DENVER MODEL

The most severe carbon monoxide episodes in Denver typically occur in winter. Carbon monoxide is emitted mainly from traffic sources (see Appendix B), and peak concentrations of CO are found very close to the traffic lanes from which they are emitted. For these reasons, exceedances of the CO standard tend to occur during the morning rush hour when the mixing layer is very thin. Since sunrise does not occur until well into the rush hour in winter, but much earlier in summer, there is less solar heating to increase the thickness of the morning mixing layer in winter. The confinement of CO in a thin mixing layer leads to high concentrations.

The winter high pollution day for which we were supplied meteorological and air quality data was 15 November 1974. DAQM simulation runs were made with meteorology from this date and emissions for 1976, 1985, and 2000. These runs were made with the photochemistry in the model suppressed to save computer time since CO is essentially inert.

The minimum mixing depth corresponding to the meteorological conditions was estimated to be only about 65 feet, much less than the summer minimum of 165 feet. The CO concentration peak, however, occurs in the region of densest traffic. In Denver the densest traffic is in the central business district, where high-rise construction ensures the occurrence of eddies and turbulence such that the mixing layer can hardly be thinner than the 165-foot summer layer. The mixing layer was thus assumed to be no thinner than 165 feet in the central business district.

Both one-hour-average and eight-hour-average predicted maximum CO concentrations were determined for comparison with the NAAQS of 35 ppm (one-hour-average) and 9 ppm (eight-hour-average). The peak concentrations, their times of occurrence, and the coordinates of the grid cell in which they occurred are given in Table III-1.

TABLE III-1. CO CONCENTRATIONS PREDICTED BY THE DENVER MODEL.
15 November 1974 Meteorology Assumed

	Peak Concentration (ppm)		Time of	Grid Cell
Year	One-Hour-Average	Eight-Hour-Average	Occurrence	(x,y Coordinates)
1976	26		7-8a.m.	42,44
	--	15	5a.m.-1p.m.	42,44
1985	17	--	8-9a.m.	42,44
	--	10	5a.m.-1p.m.	42,44
2000	4	--	6-7a.m.	56,58
	--	3	5a.m.-1p.m.	56,58

These results show that, even averaged over four square miles, violations of the eight-hour CO standard now occur. By 1985 only a minimal exceedance is predicted, and by 2000 the Denver atmosphere is predicted to be in good compliance if the assumptions of the emissions projections are correct. (Achievement of AP-42 emission factors is the most important assumption.) Since CO peaks occur very close to the sources, it may be presumed that both one-hour and eight-hour violations that cannot be resolved on the simulation grid will occur.

Both the 1976 and 1985 peaks are predicted to occur at grid cell 42,44, which is in the vicinity of the C.A.R.I.H. monitoring station. In the year 2000 the peak is found at 56,58, in the vicinity of Barr Lake along Interstate 80S.

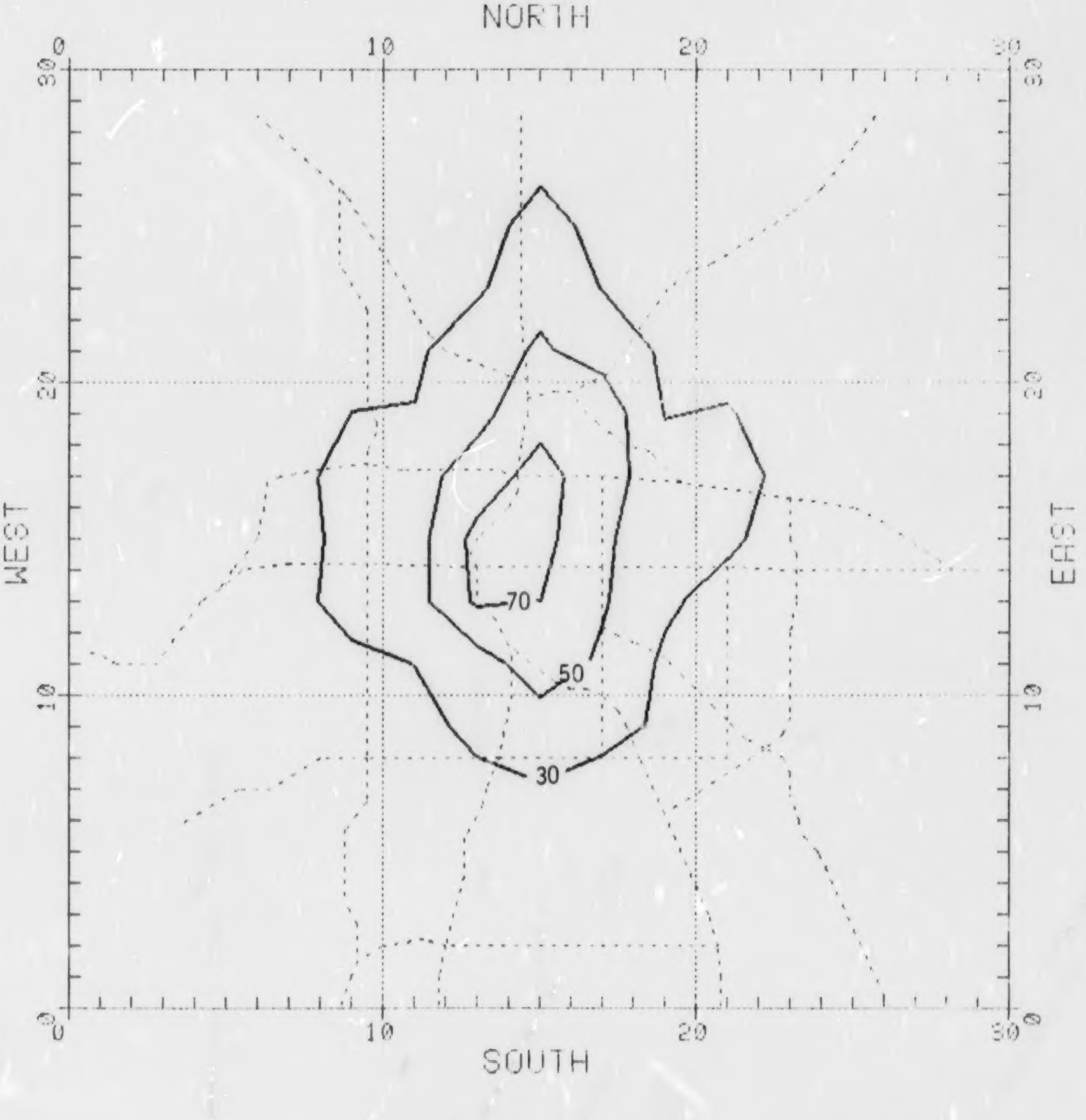
C. BASE CASE NO_2 AND PARTICULATE CONCENTRATIONS PREDICTED BY THE CDM

The CDM was run for the years 1974, 1980, 1985, 1990, and 2000. The receptor network used was a 15 x 15 grid of receptors spaced two miles apart. Isopleth maps were prepared by a computer plotting program that interpolated contours between the receptors; isopleths of predicted NO_2 concentrations are shown in Figure III-3. These maps may be compared with Figures 22 through 31 of the Joint Regional Planning Program (JRPP) Air Quality Assessment Statement (Colorado Division of Highways, 1976). These isopleth maps are given in units of $\mu g/m^3$, whereas in the JRPP document NO_2 concentrations are given in ppm.

The isopleth maps show that the highest concentrations of both NO_2 and particulates are in the vicinity of major highways and the downtown area. This observation leads to the conclusion that the major source of these pollutants is traffic. Other features of the maps are the NO_2 peak at Stapleton Airport, and particulate peaks in the vicinity of Golden and the intersection of U.S. 285 and State Highway 121.

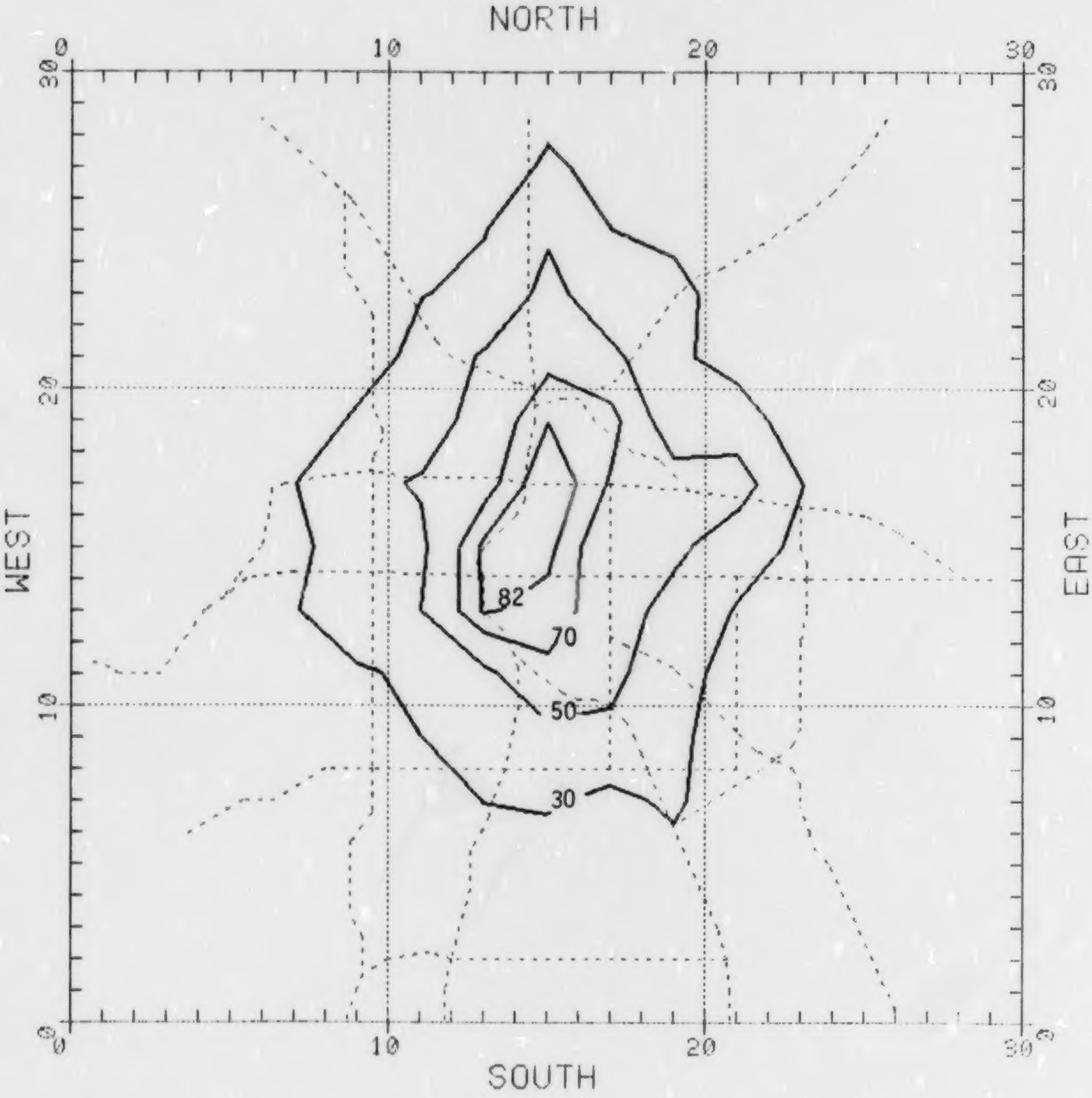
The National Ambient Air Quality Standard (NAAQS) for NO_2 is 0.05 ppm for an annual average, which converts to 82 $\mu g/m^3$ at Denver's altitude and annual average temperature. For annual average particulate concentrations the NAAQS is 75 $\mu g/m^3$, but the Colorado state air quality standard of 45 $\mu g/m^3$ is more stringent.

Figure III-4 shows how NO_2 concentrations predicted by CDM change from 1974 to 2000. (The boundaries of the subregions listed in Figure III-4 are shown in Figure IV-1.) In 1974 no exceedance of the NAAQS is calculated by the model: the maximum annual average concentration given by the model is


NORTH
SOUTH
WEST
EAST
0
10
20
30
70
50
30

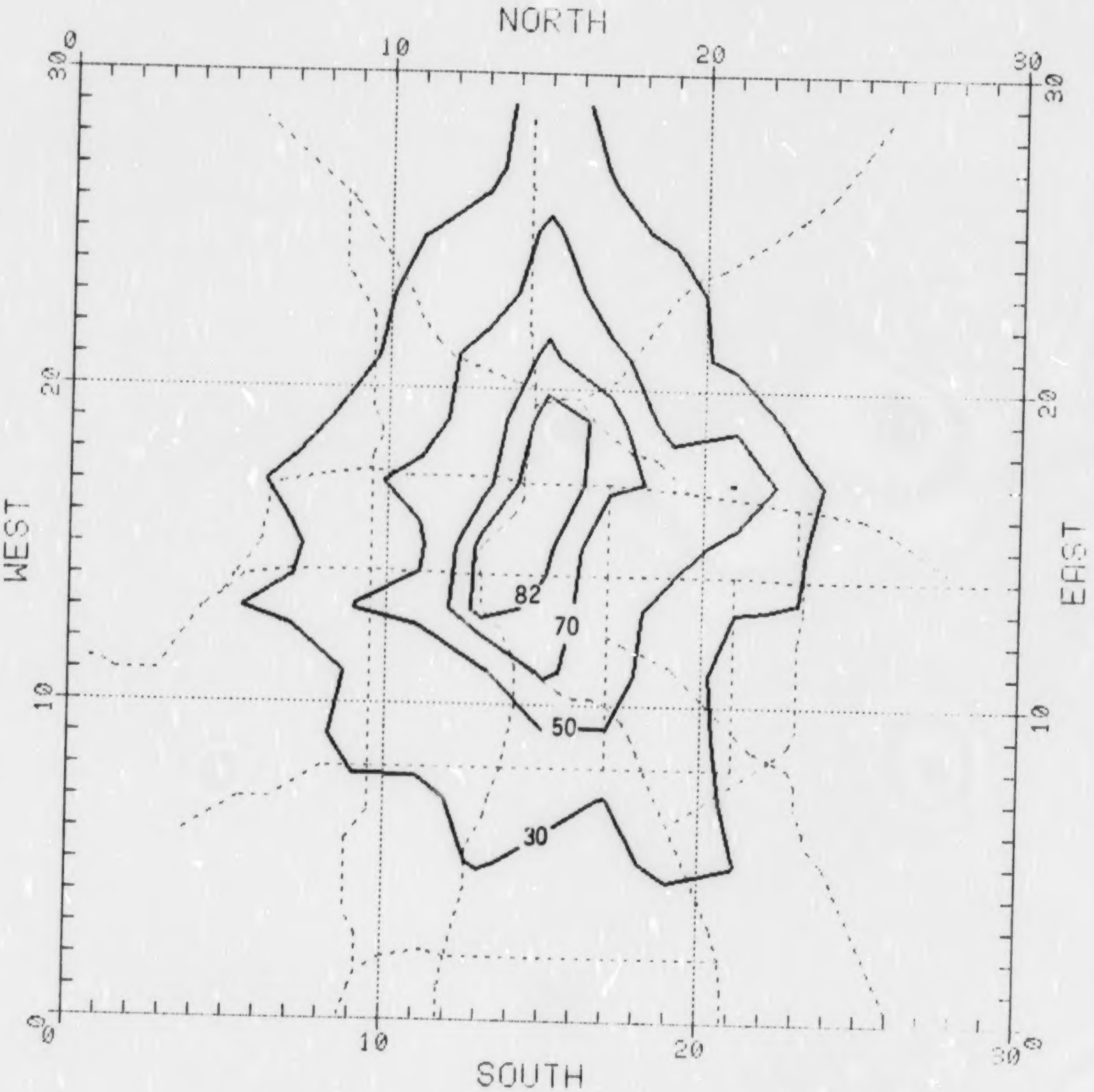
(a) Year 1974

FIGURE III-3. ISOPLETHS IN μg/m^3 OF CALIBRATED ANNUAL AVERAGE NO$_2$ CONCENTRATIONS PREDICTED BY CDM FOR VARIOUS YEARS



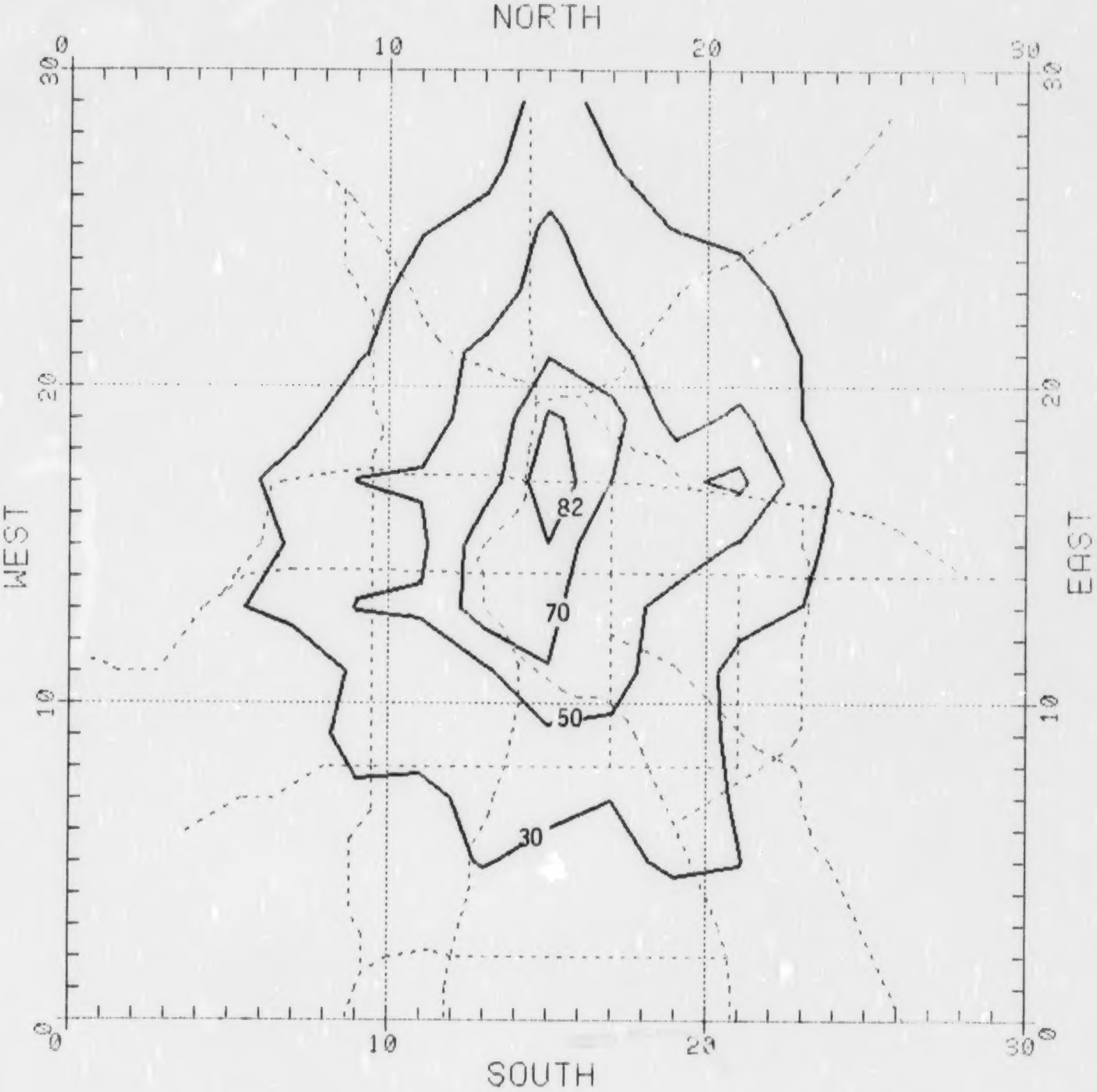
(b) Year 1980

FIGURE III-3. (Continued)



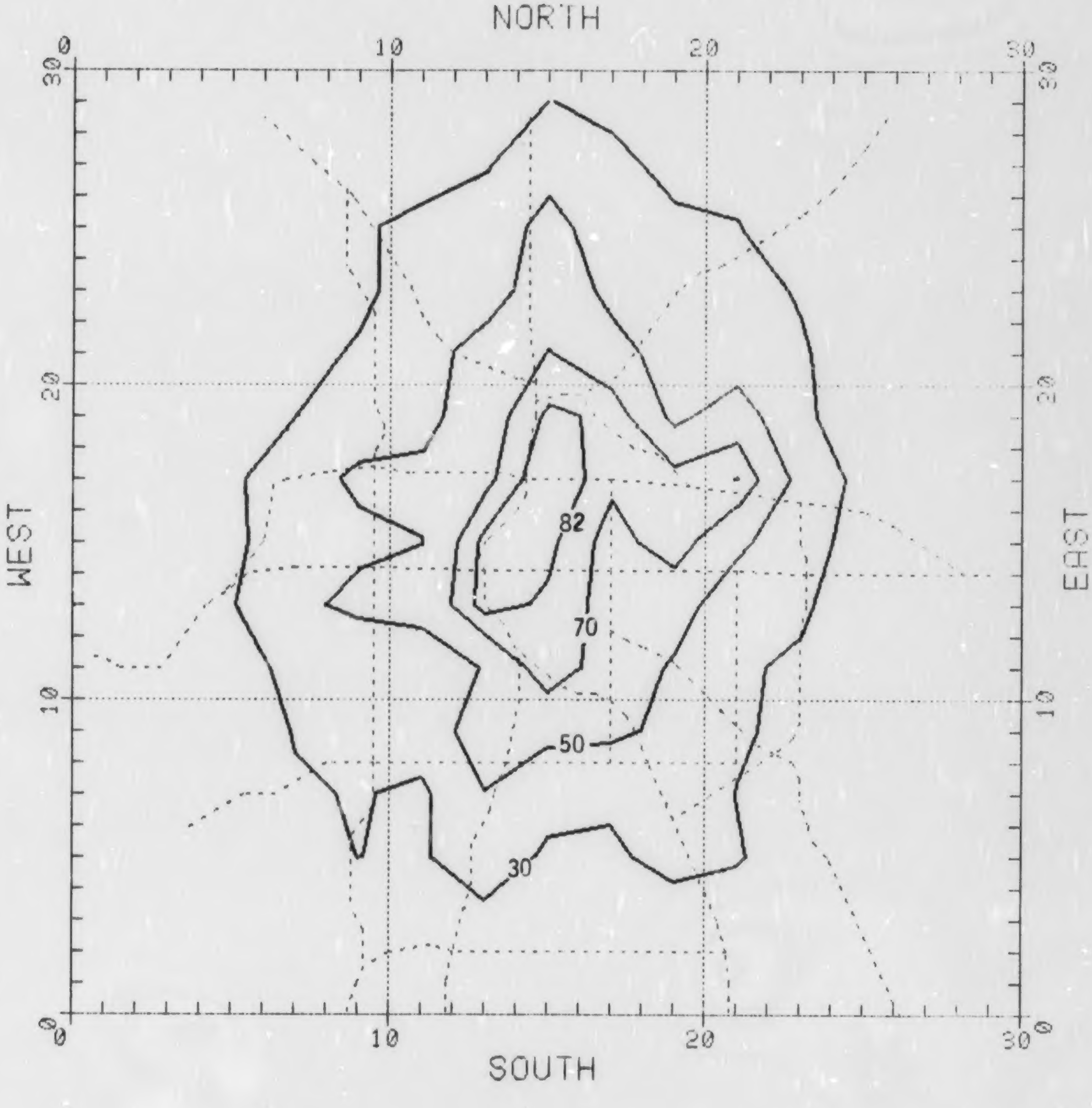
(c) Year 1985

FIGURE III-3. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
82
70
50
30

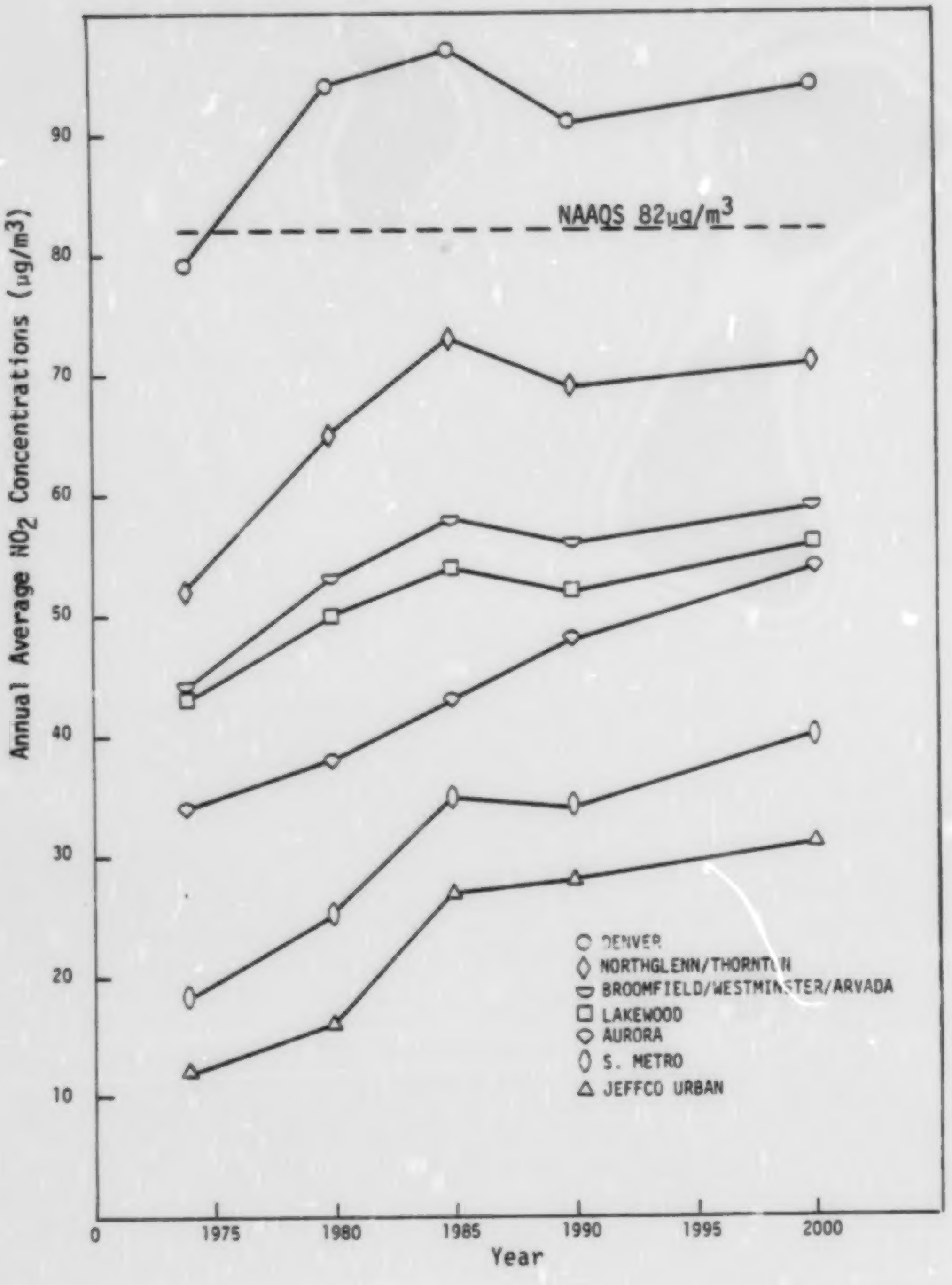
(d) Year 1990

FIGURE III-3. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
82
70
50
30

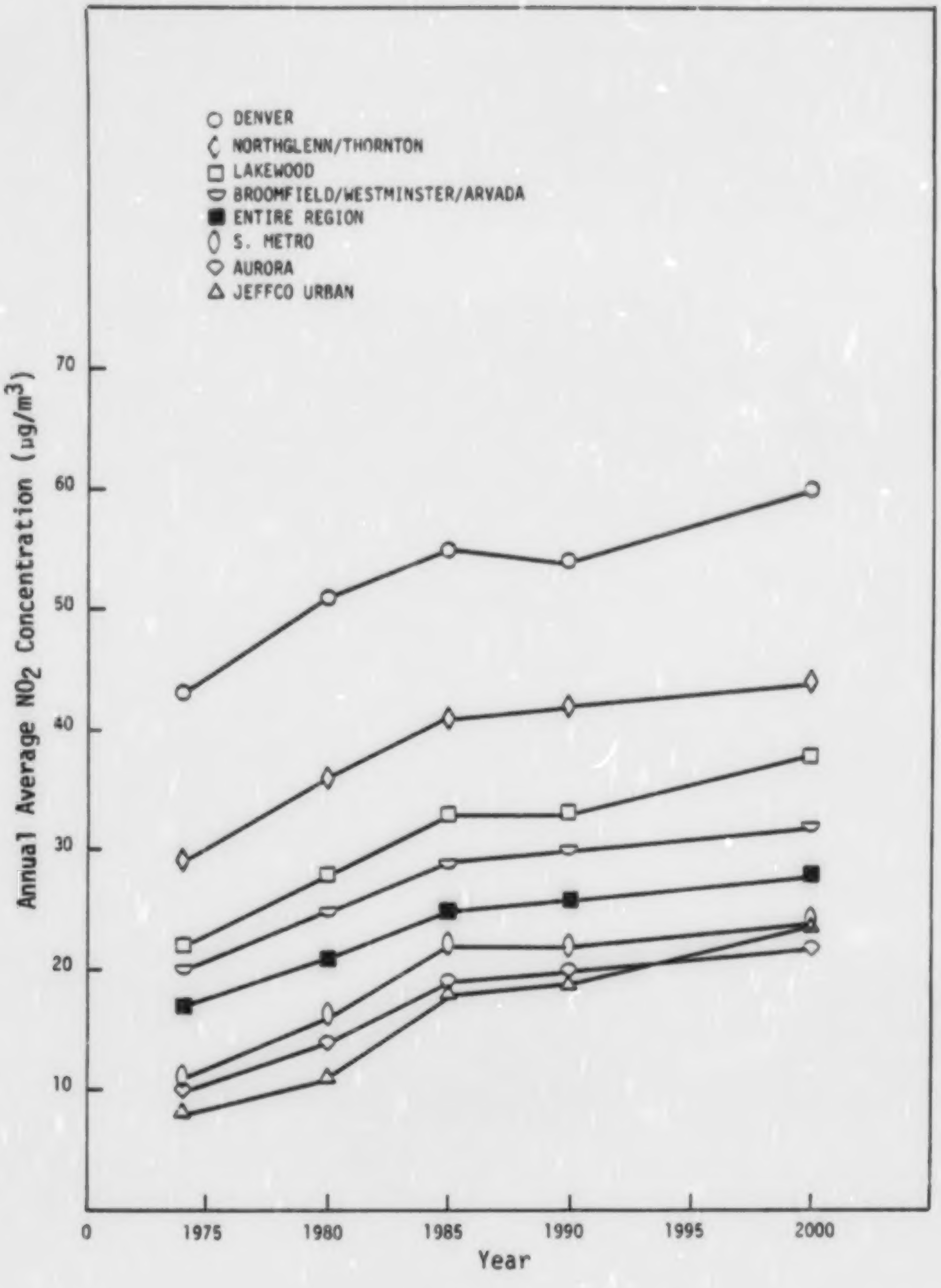
(e) Year 2000

FIGURE III-3. (Concluded)



(a) Maximum Concentration in Any Grid Cell Within Subregion

FIGURE III-4. NO$_2$ CONCENTRATIONS PREDICTED BY CDM FOR 1974 TO 1990



(b) Average Concentration in Subregion

FIGURE III-4. (Concluded)

79 μg/m^3. This maximum is, in fact, determined by the one calibration point available. It is not, therefore, a prediction in any real sense. In 1980 some exceedances are predicted, and these persist through 2000. Table III-2 shows the number of square miles over exceedance of the NAAQS is predicted. This table contains data from our use of CDM from the Air Quality Assessment Statement (CDH, 1976) and from the 1976 report to the Public by the Colorado Department of Health (1976b).

The agreement between the results of this CDM study and those of previous studies is fairly good. The discrepancies are probably the result of the use of different arrays of receptors and the interpolation of contours by hand in the previous studies.

The predicted exceedances of the NAAQS for NO_2 should be viewed with skepticism in the light of the propensity of the CDM to mispredict NO_2 as discussed in Appendix A. The CDM predictions are made assuming that all NO_x is in the form of NO_2. Since the emissions are mainly NO, and are not all converted to NO_2, the calibration used to match the predictions and observations can only be valid at the place and time for which the calibration constant was determined. The Denver Model distinguishes between NO and NO_2 and could predict annual average NO_2 concentrations, but extensive computation would be required. Denver Model results for single days indicate, however, that the assumption underlying CDM that concentrations are proportional to emissions is invalid for NO_2. DAQM base case simulations were examined for inferences as to NO_2 dependence on emissions. Time variations of NO_2 concentrations predicted by the Denver Model at CAMP, which has the peak NO_2 concentration according to CDM, are presented in Figure III-5 for 3 August 1976 and 2000. Also presented in this figure is the 1976 NO_2 concentration multiplied by the 2000/1976 NO_x regionwide average ratio of NO_x emissions. This represents a prediction consistent with CDM assumptions if CAMP NO_2 depends on sources at a distance, but assuming all NO_x acts as NO_2. If CAMP NO_2 depends more on local sources, the appropriate 200/1976 emissions ratio would be that for the grid cell containing the CAMP location. This ratio is about 1.015. Although this number is very near unity, it is greater than one and its use would lead to a

TABLE III-2. AREA OF EXCEEDANCE OF NAAQS FOR NO_2

(in square miles)

Year	Predicted by CDM in This Project	Assessment Statement*	Report to Public†
1974	0	2.1	1
1980	9	--	11
1985	14	19.1	16
1990	4	14.7	--
2000	13	23.0	--

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*Colorado Division of Highways (1976).

†Colorado Department of Health (1976).

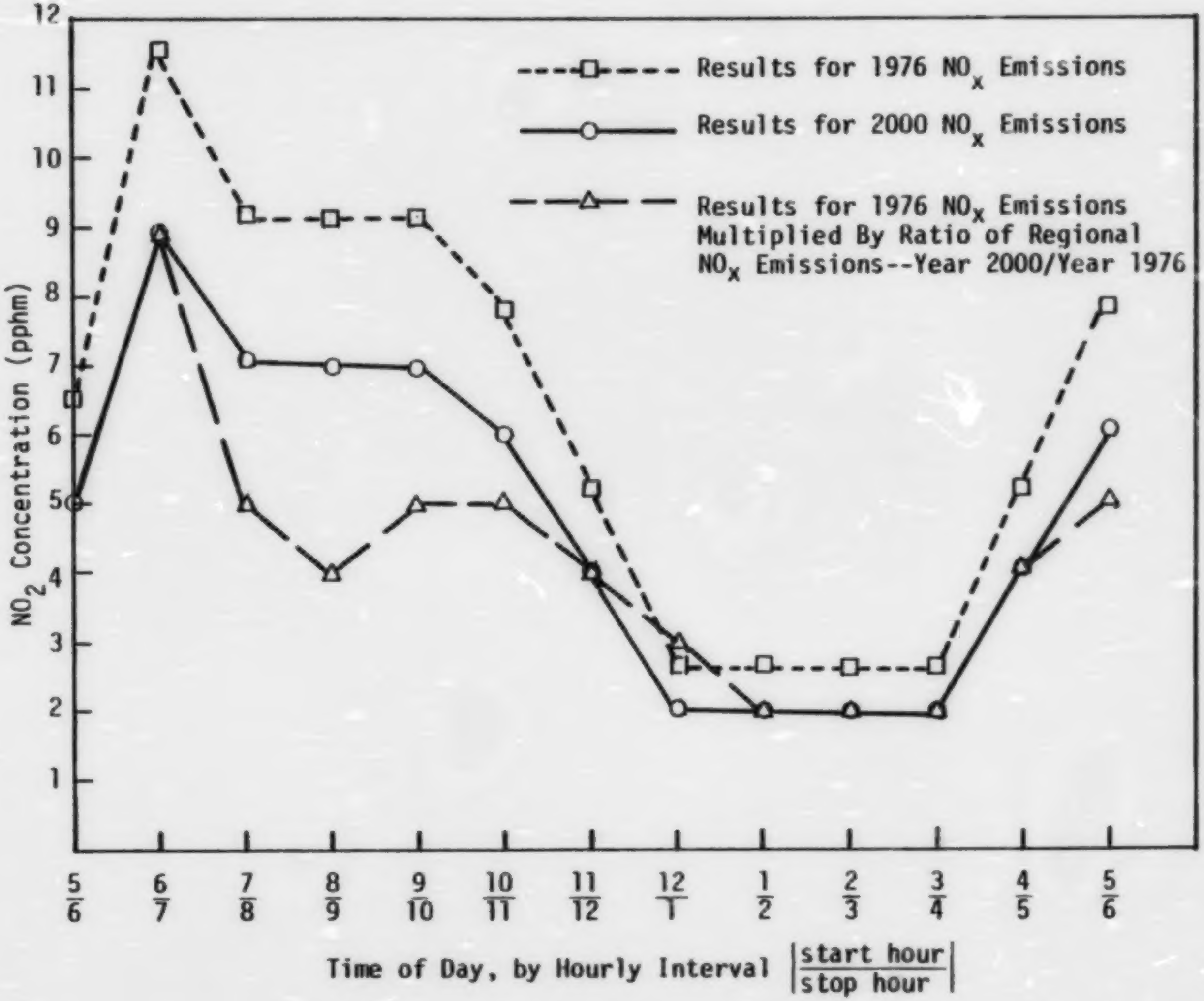


FIGURE III-5. NO$_2$ CONCENTRATIONS AT THE CAMP SITE IN DOWNTOWN DENVER PREDICTED BY THE DENVER MODEL. 3 August 1976 meteorology assumed.

prediction of increased NO_2. It can be seen that the photochemical simulation leads to a prediction of a 22 percent decrease in peak NO_2 and an 18 percent decrease in average NO_2.

This analysis does not prove that annual average NO_2 concentrations would decrease with an increase in NO_x emissions, but it certainly suggests this possibility and lends credence to the skepticism noted above. NO_2 13-hour-average predictions using 3 August computations for CAMP for each year calibrated with present annual average at CAMP are presented in the summary in Table III-3 at the end of this chapter.

Figure III-4 shows the maximum and average NO_2 concentrations predicted by the CDM for the city of Denver and various subregions around Denver. (These subregions were chosen for study in connection with the sensitivity analysis in Chapter IV.) These figures show that the CDM predicted maximum in the entire modeling region is 97 $\mu g/m^3$ in 1985 in central Denver. We believe that, considering the likely amount of overprediction of NO_2 by the CDM, this result does not represent a firm prediction of an exceedance of the NAAQS.

It may be seen from Figure III-4 that, while NO_2 concentrations generally increase between 1974 and 2000, concentrations in some areas decrease between 1985 and 1990. This effect is not related to total population, as can be seen from Figure III-6, which shows the projected populations of these areas. All areas show a continuous increase over these years, with all except Denver and Jefferson County Urban having a growth rate of about 2-1/2 percent per year.

The break in the NO_2 trends in 1985 most probably stems from one of two causes:

> The emissions inventories were made up by different agencies using different splits between single and multi-family dwellings (although with the same total population projections).

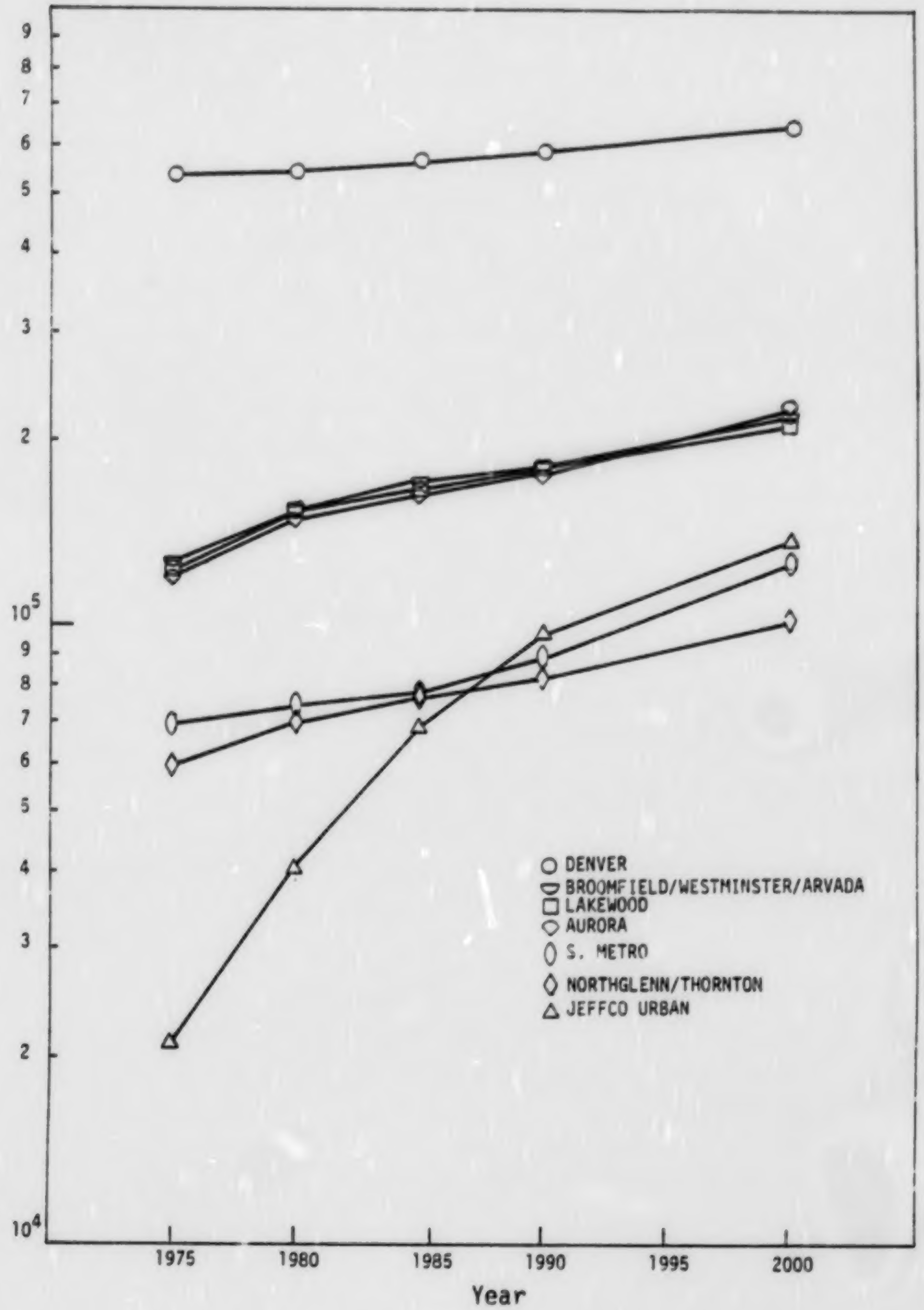


FIGURE III-6. POPULATION PROJECTIONS FOR THE DENVER AREA, 1975 to 2000

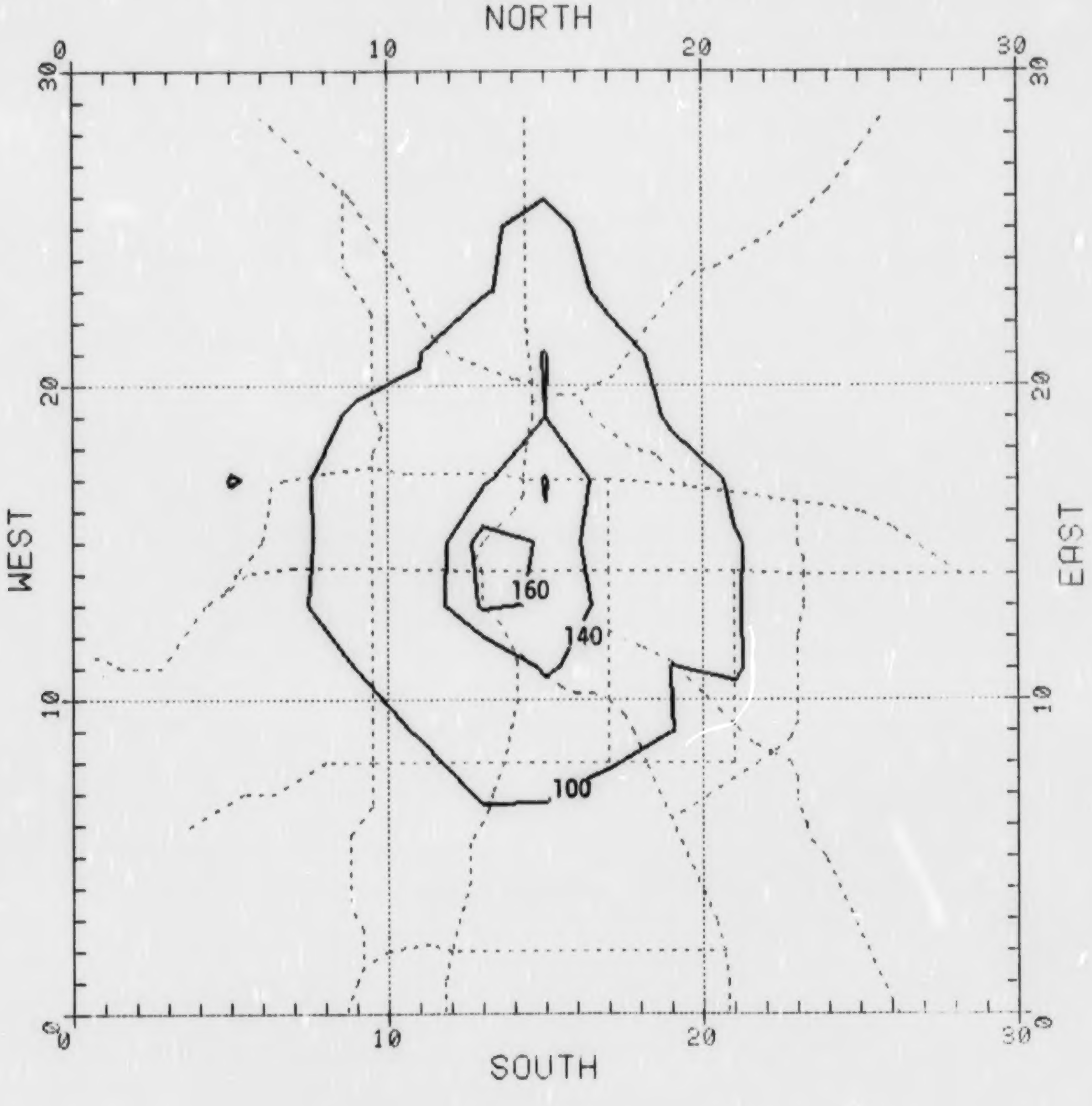
By 1985-1990, NO_x emissions controls on light-duty vehicles will have reached their maximum effectiveness. After this, the increase of overall VMT will cause NO_x emissions to rise again.

Figure III-7 shows isopleths of particulate concentrations predicted by the CDM for 1974 through 2000. The state air quality standard is exceeded over the entire area for all years. The NAAQS is exceeded over 460 square miles in 1974 (51 percent of the region), 548 square miles (61 percent) in 1980, 668 square miles (74 percent) in 1985, 716 square miles (80 percent) in 1990 and 724 square miles (80 percent) in 2000.

Figure III-8 shows the maximum and average particulate concentrations predicted for the various subregions by the CDM. Both Lakewood and Jefferson County Urban show large increases between 1985 and 1990. The reason for this is not clear; it is not attributable to the increased construction activity attendant on the area's rapid growth, since Figure III-6 shows that population increases in all periods. Another contributing factor could be the difference in population assumptions used by the two groups who assembled the emissions inventories.

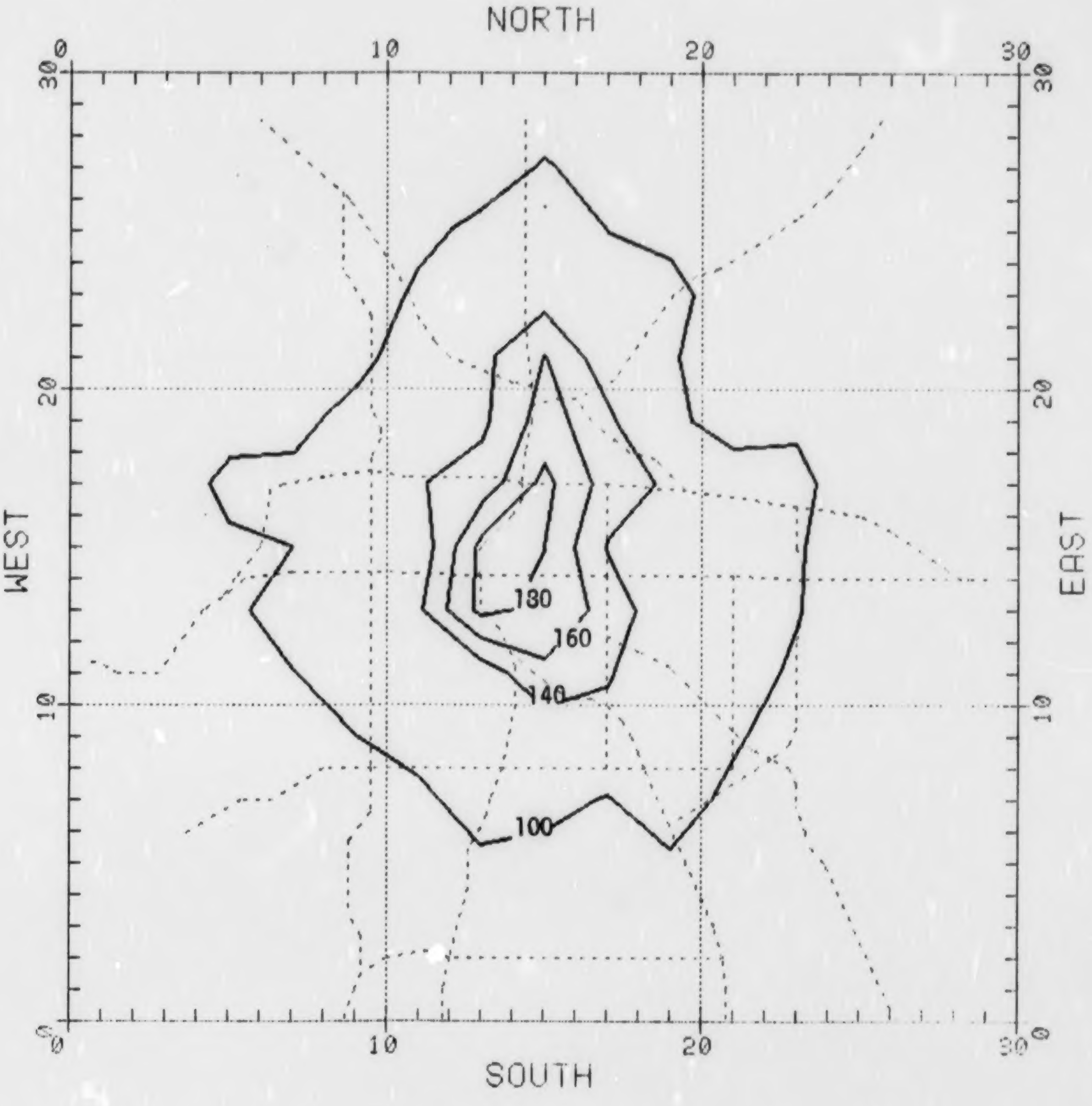
Another way of looking at these base case runs is to examine the incremental changes in concentration levels which occur from one year to another. Figures III-9 and III-10 show contours of these incremental changes for NO_2 and particulates.

Examination of Figure III-9 shows that during 1974 to 1980 the largest increases are forecast for Commerce City, Stapleton Airport, and S.E. Denver. In 1980 to 1985, the largest increases are expected at Stapleton Airport and in S.E. Denver again, and also in S.W. Denver. Between 1985 and 1990, it is predicted that concentrations in a large area surrounding downtown Denver will actually decrease, while substantial increases are expected in the northeast, around the Rocky Mountain Arsenal. In 1990 to


NORTH
SOUTH
WEST
EAST
0
10
20
30
160
140
100

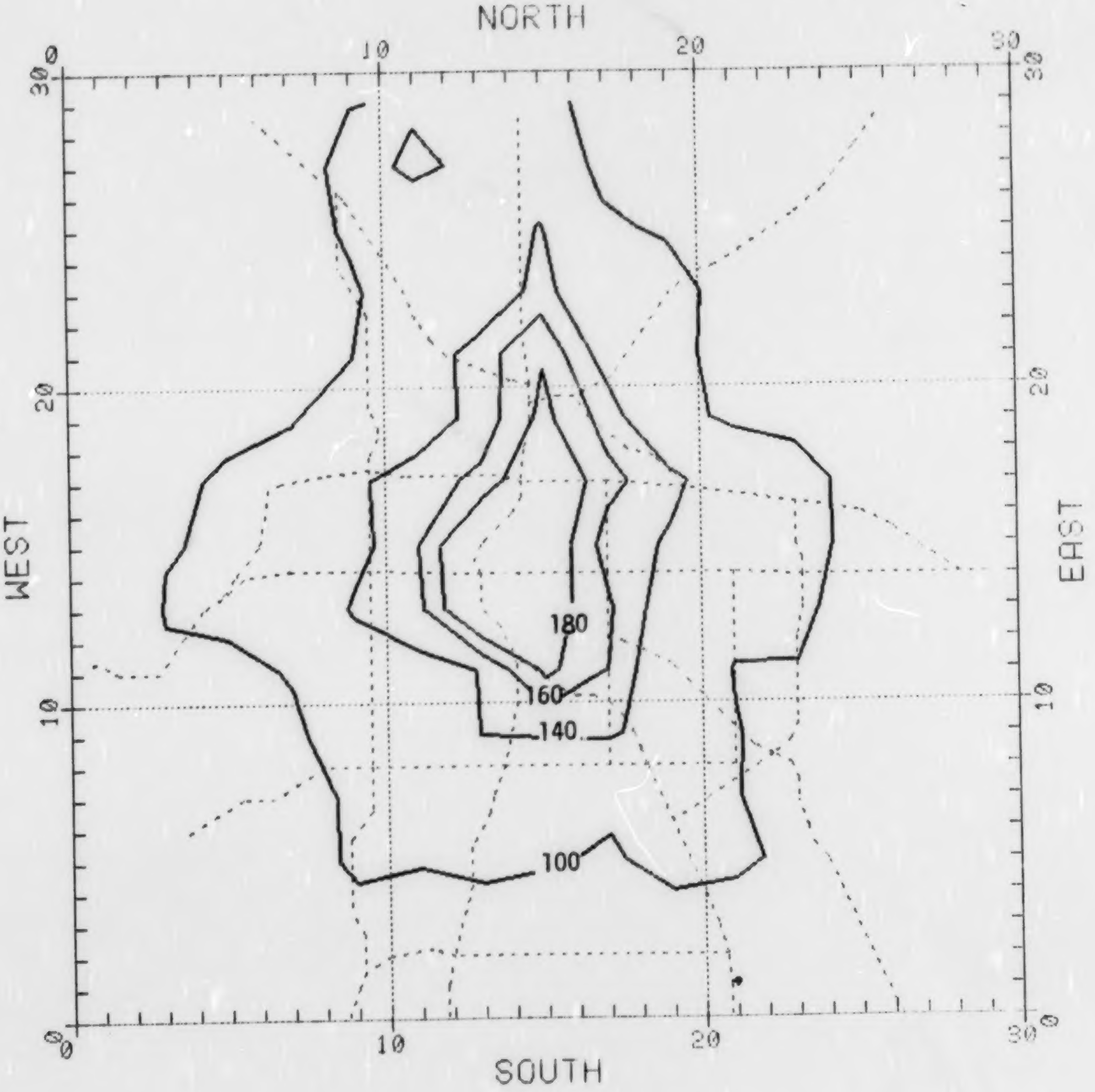
(a) Year 1974

FIGURE III-7. ISOPLETHS IN μg/m^3 OF CALIBRATED ANNUAL AVERAGE PARTICULATE CONCENTRATIONS PREDICTED BY CDM FOR VARIOUS YEARS



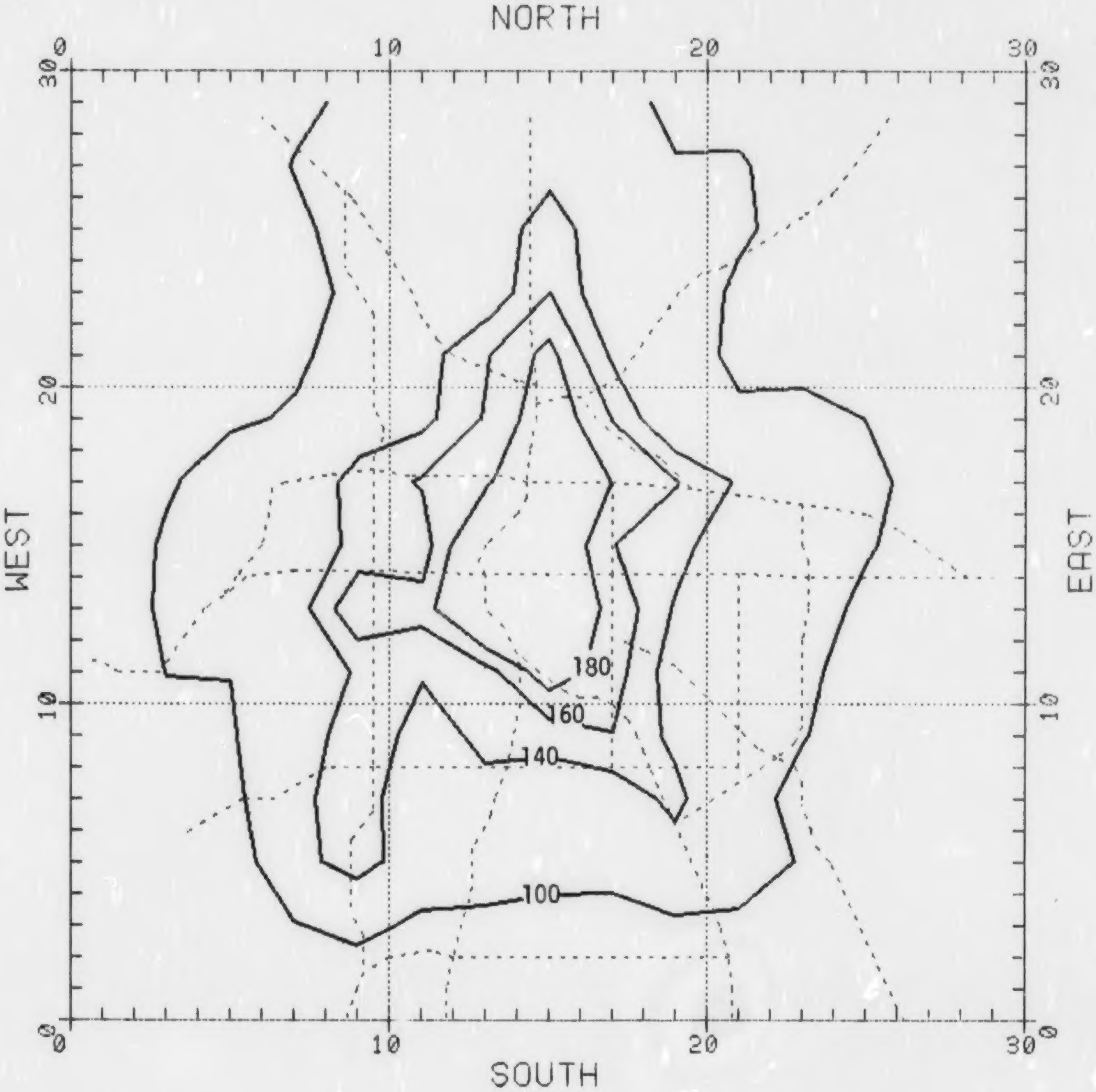
(b) Year 1980

FIGURE III-7. (Continued)



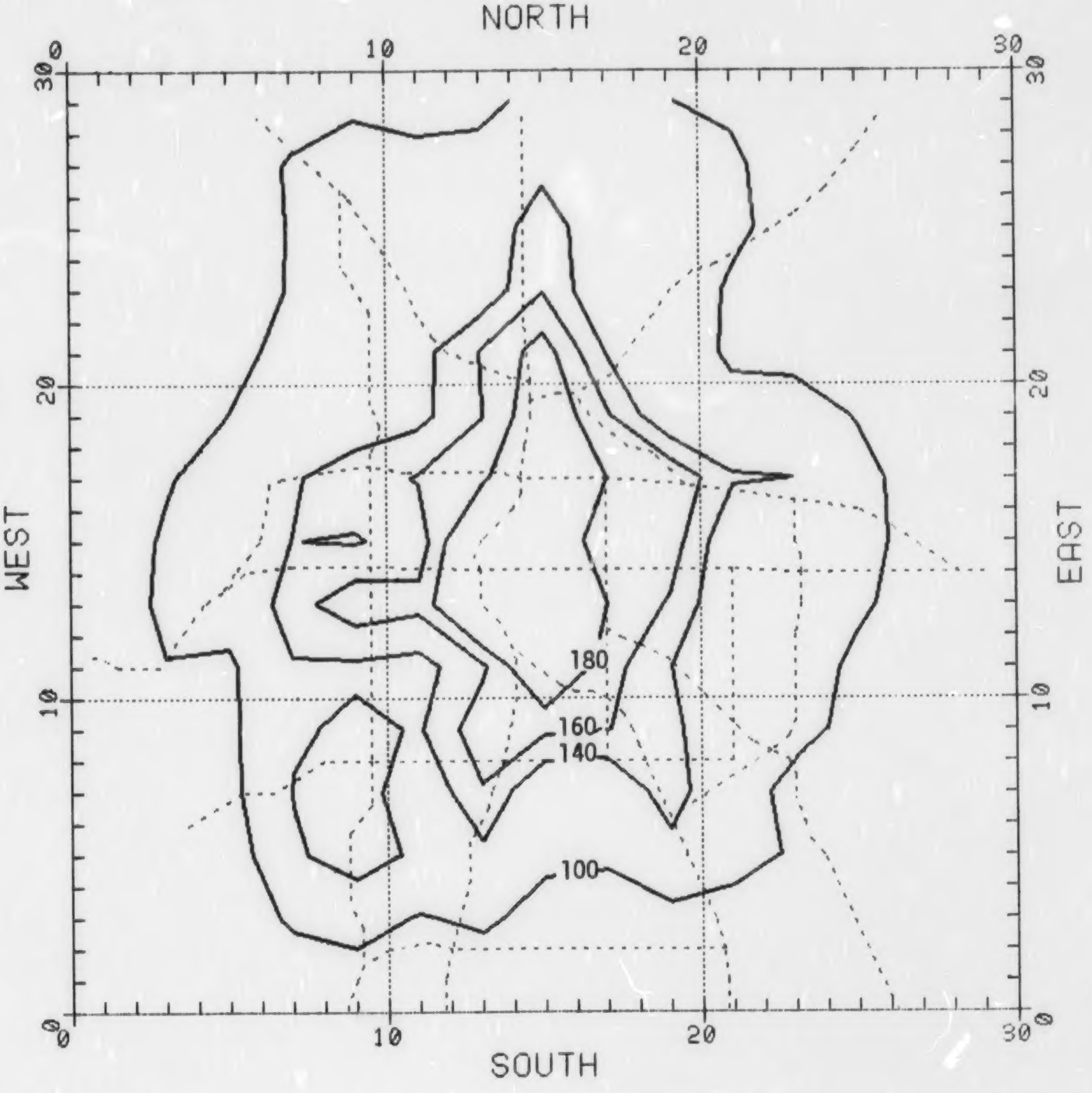
(c) Year 1985

FIGURE III-7. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
180
160
140
100

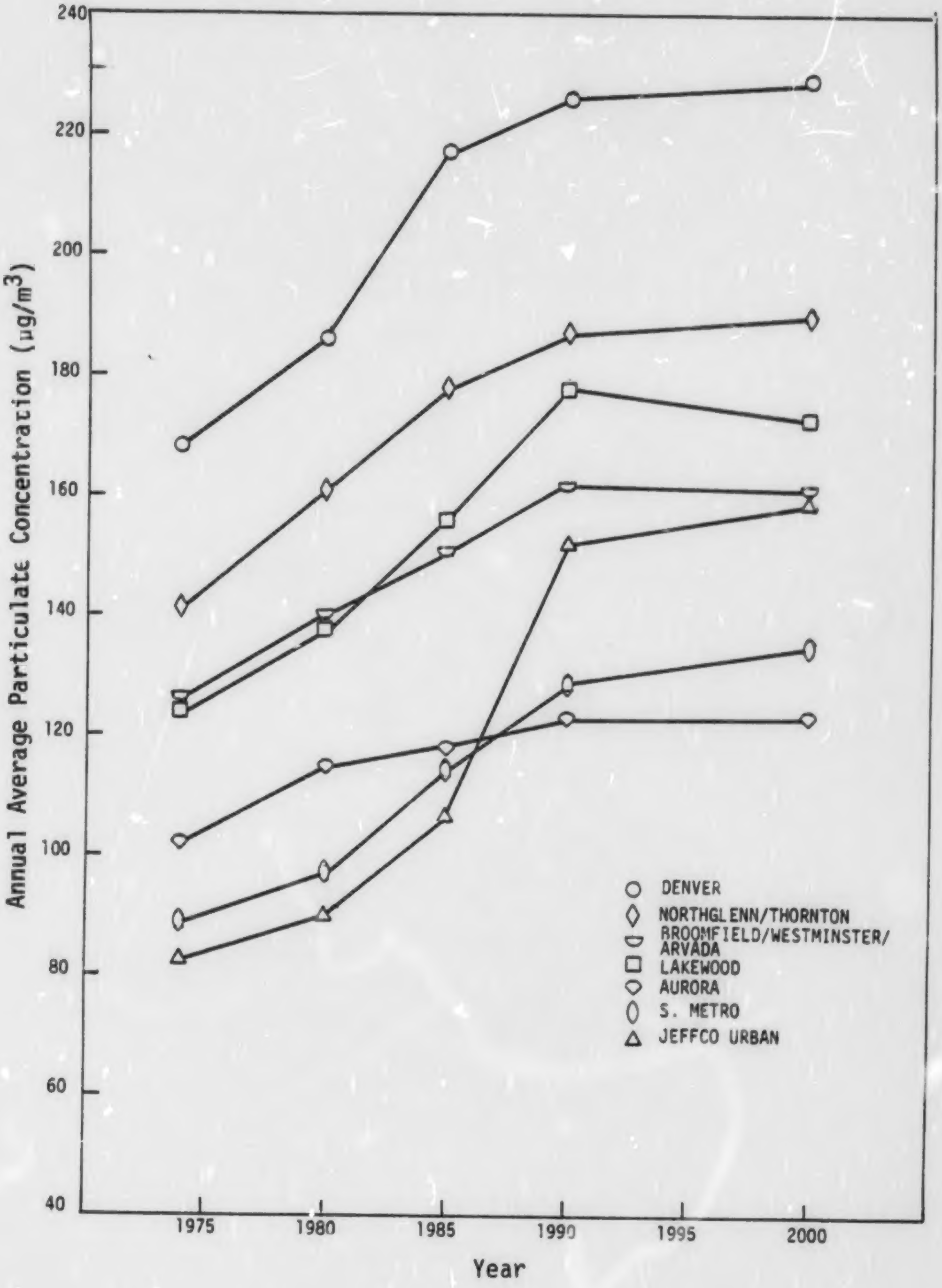
(d) Year 1990

FIGURE III-7. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
180
160
140
100

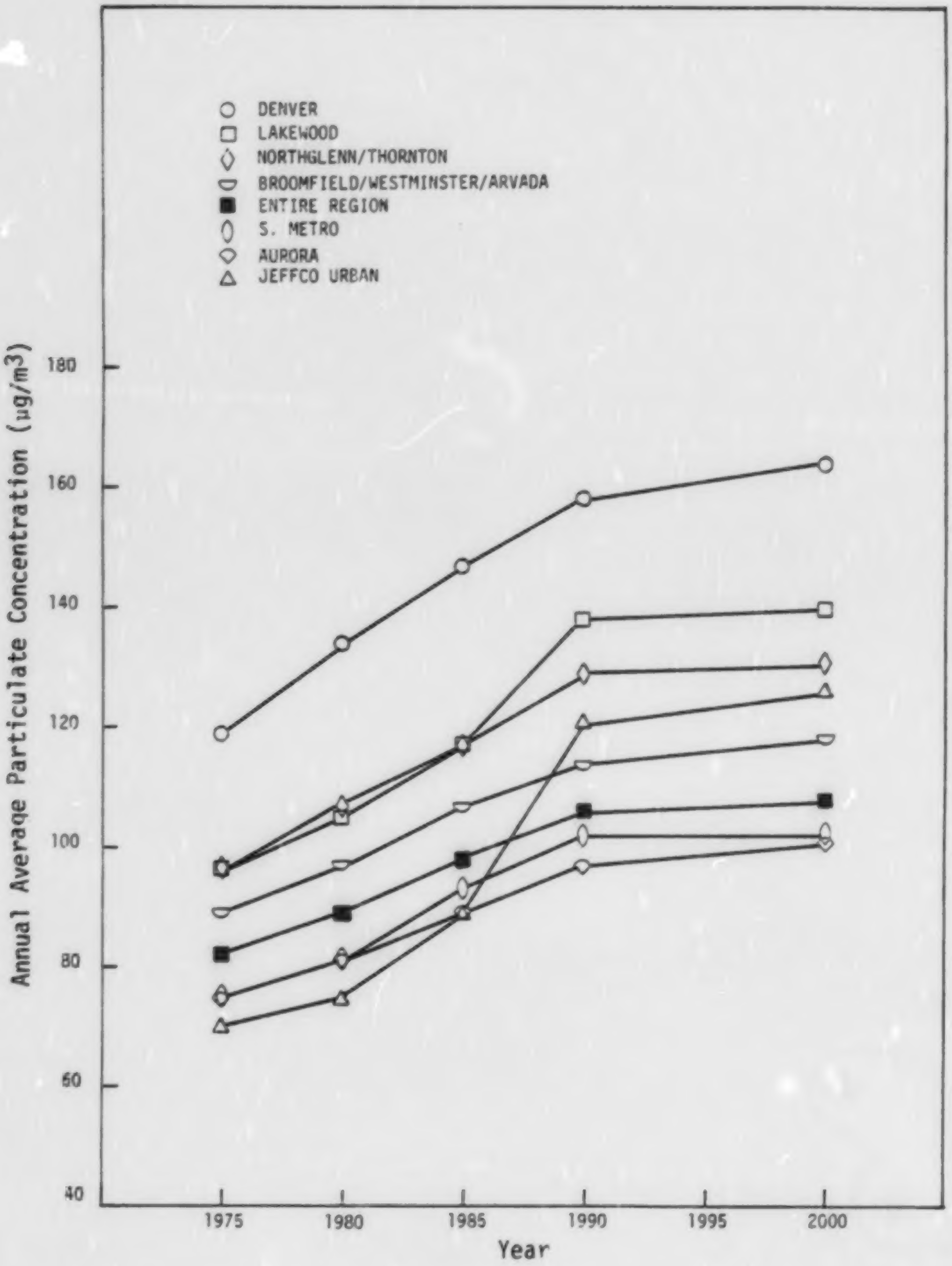
(e) Year 2000

FIGURE III-7. (Concluded)



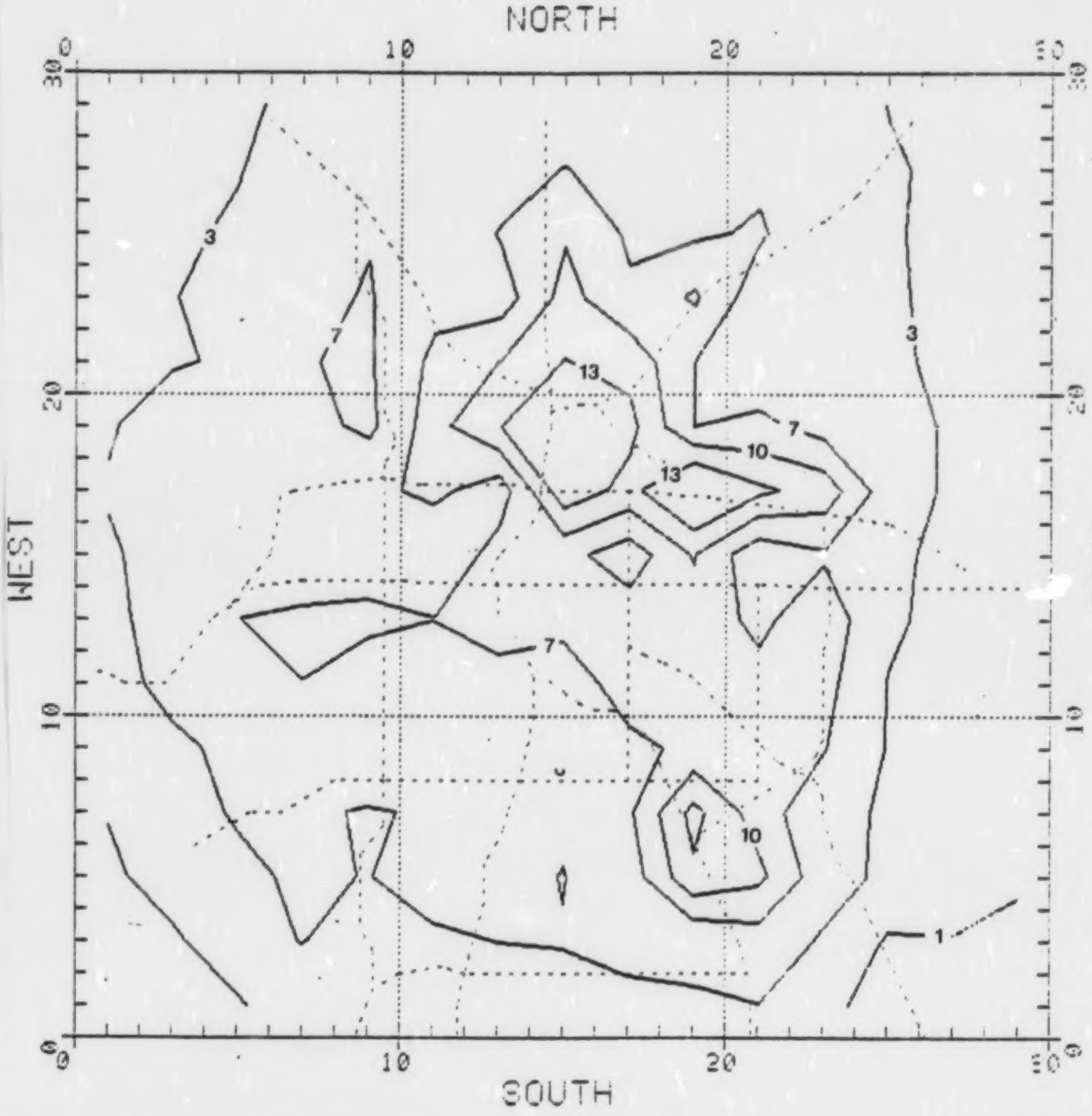
(a) Maximum Concentration in Any Grid Cell Within Subregion

FIGURE III-8. PARTICULATE CONCENTRATIONS PREDICTED BY CDM FOR 1974 TO 2000



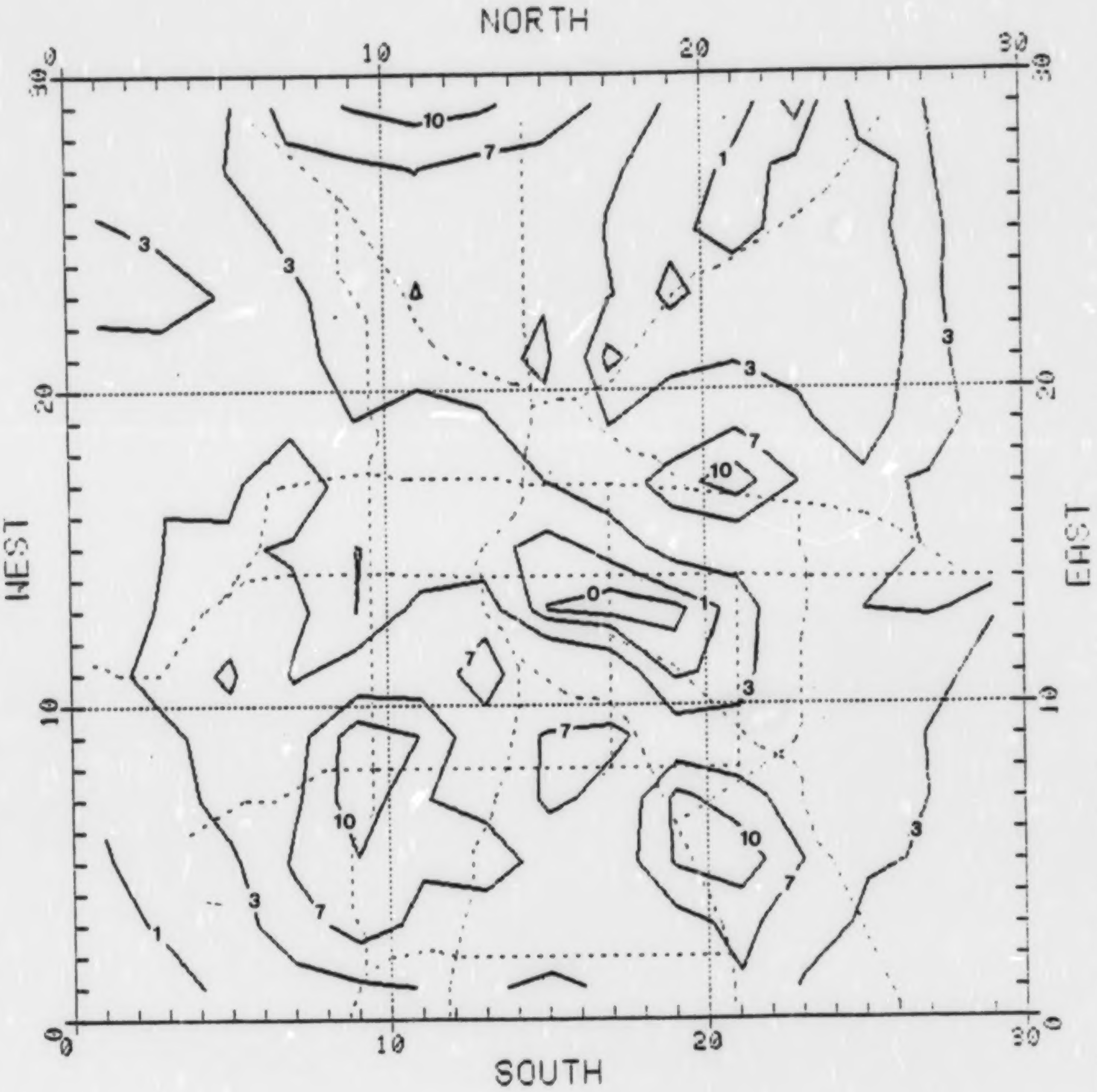
(b) Average Concentration in Subregion

FIGURE III-8. (Concluded)


NORTH
SOUTH
WEST
EAST
0
10
20
30
3
7
10
13
1

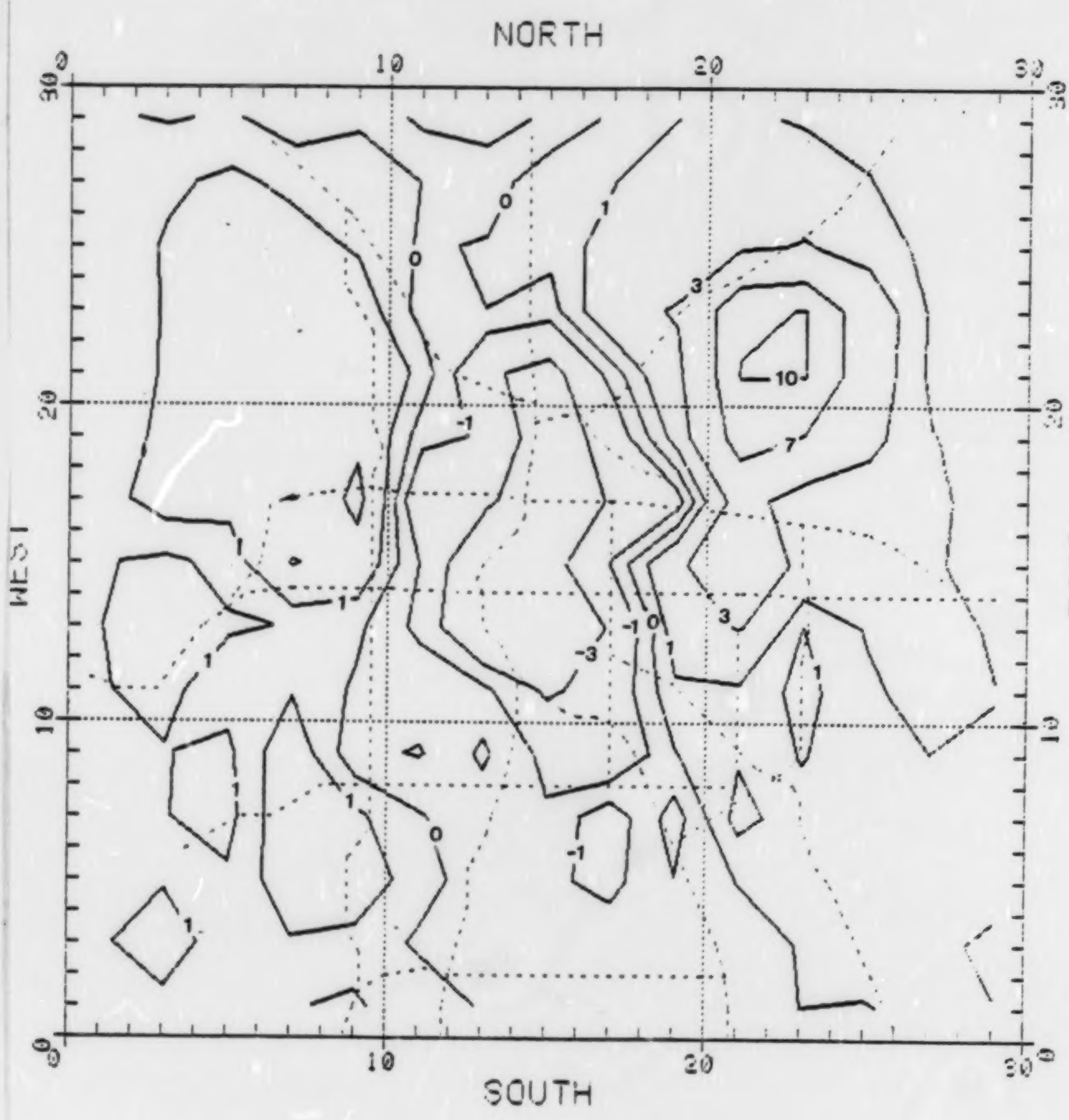
(a) 1974 to 1980

FIGURE III-9. INCREMENTAL CHANGES IN NO_2 CONCENTRATIONS PREDICTED BY CDM. NO_2 concentrations in $\mu g/m^3$.


NORTH
SOUTH
WEST
EAST
0
10
20
30
1
3
7
10
0

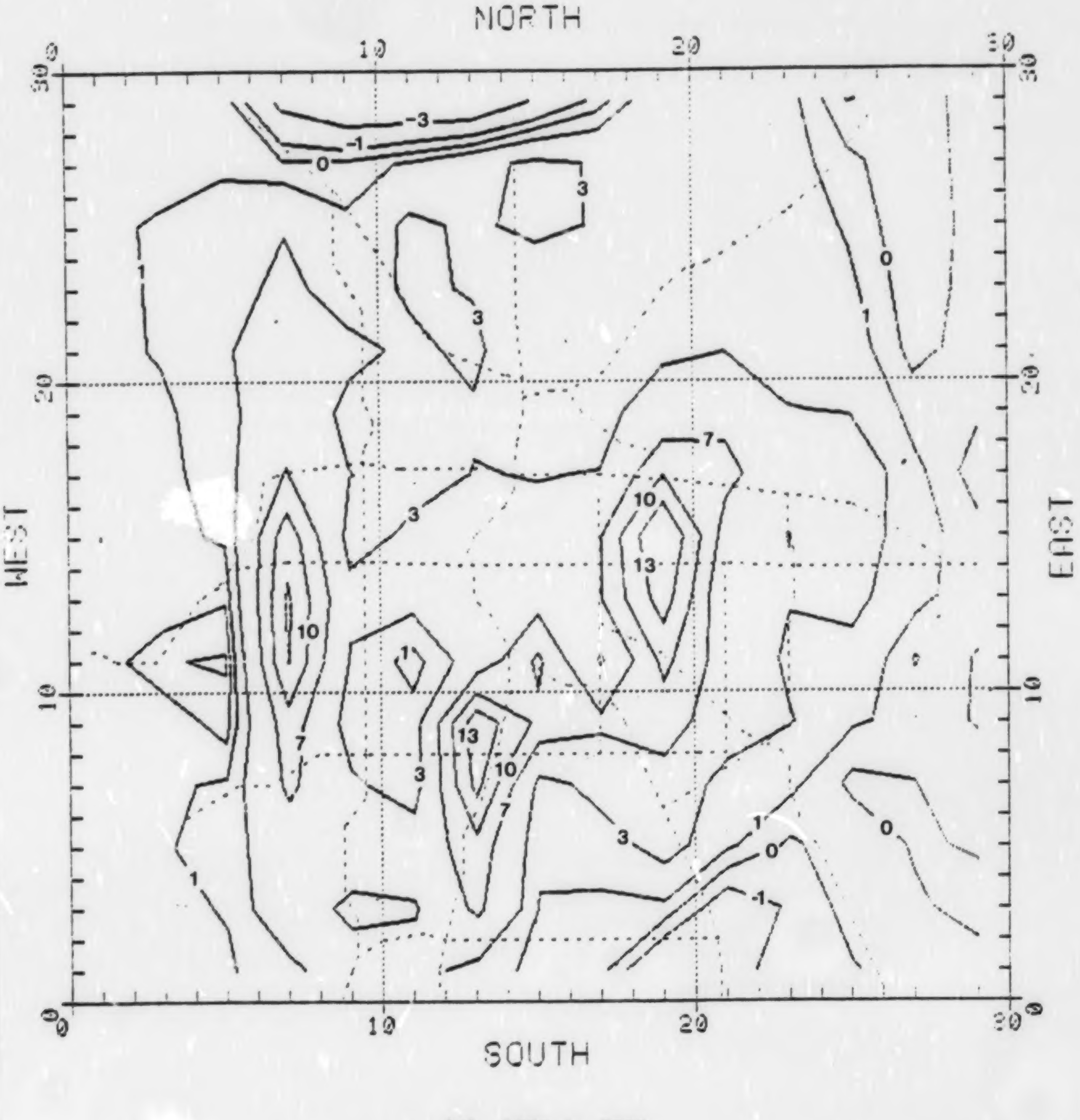
(b) 1980 to 1985

FIGURE III-9. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
0
1
3
10
7
-1
-3
-1

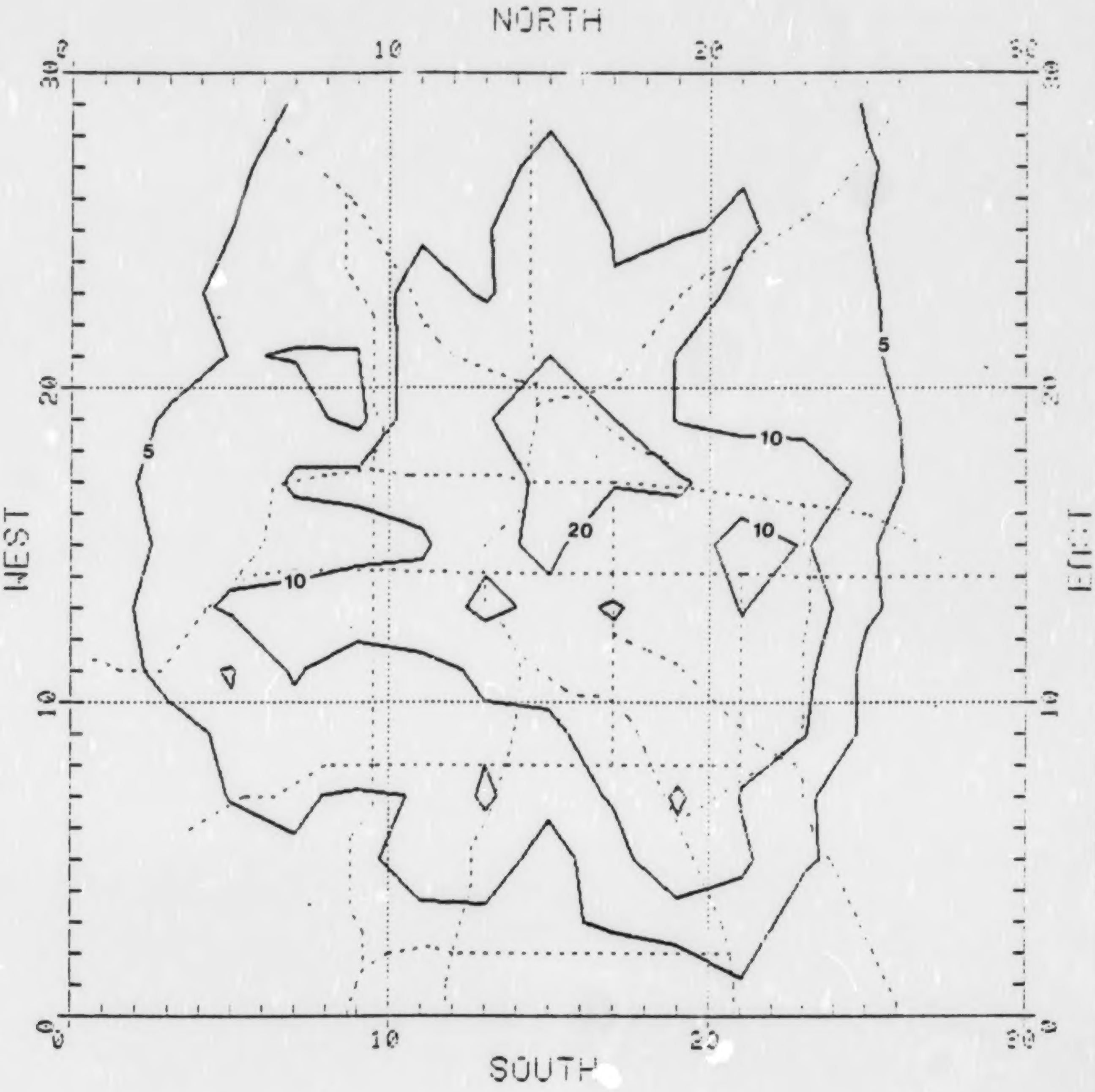
(c) 1985 to 1990

FIGURE III-9. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
-3
-1
0
1
3
7
10
13

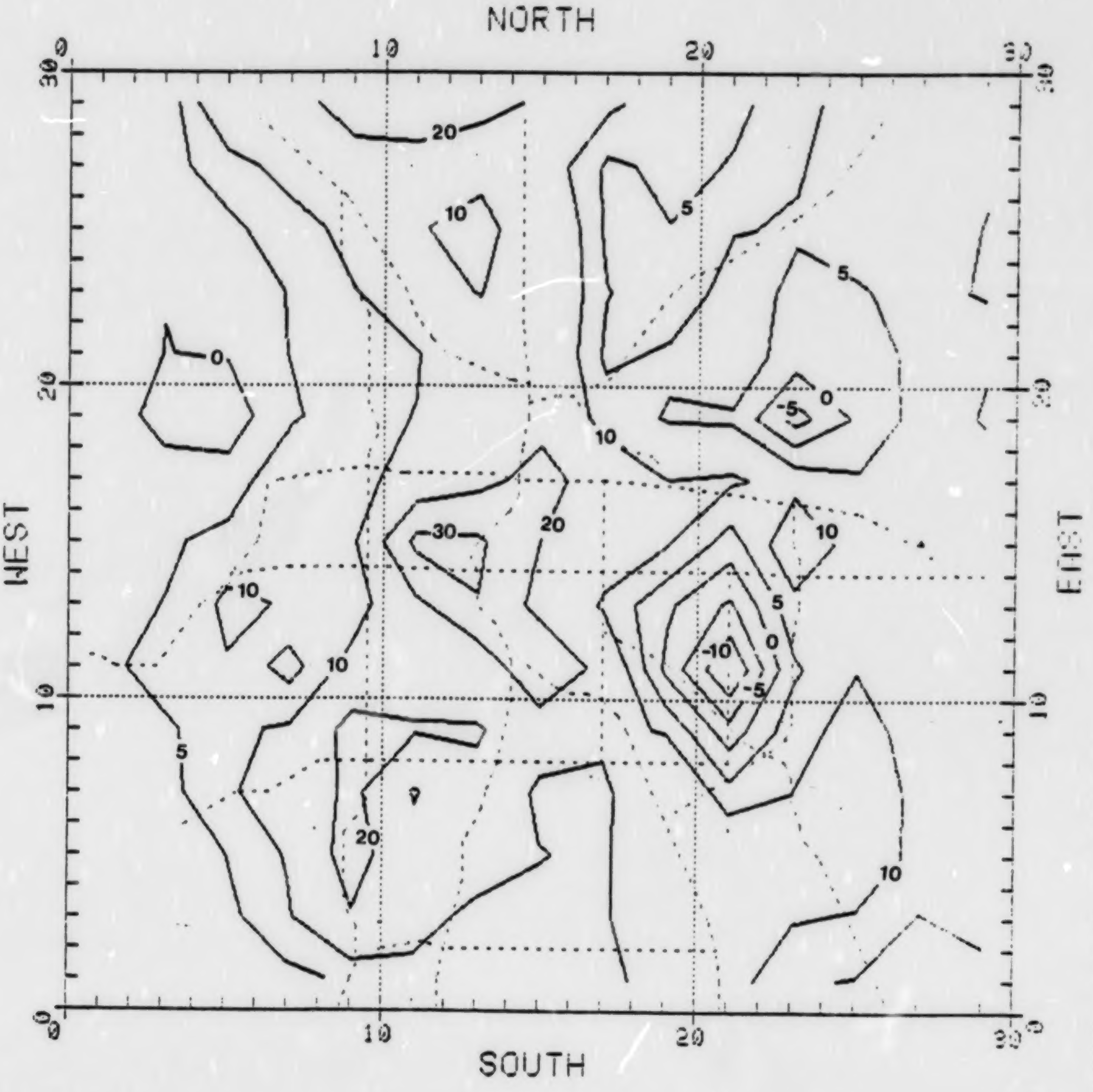
(d) 1990 to 2000

FIGURE III-9. (Concluded)


NORTH
SOUTH
WEST
EAST
0
10
20
30
5
10
20

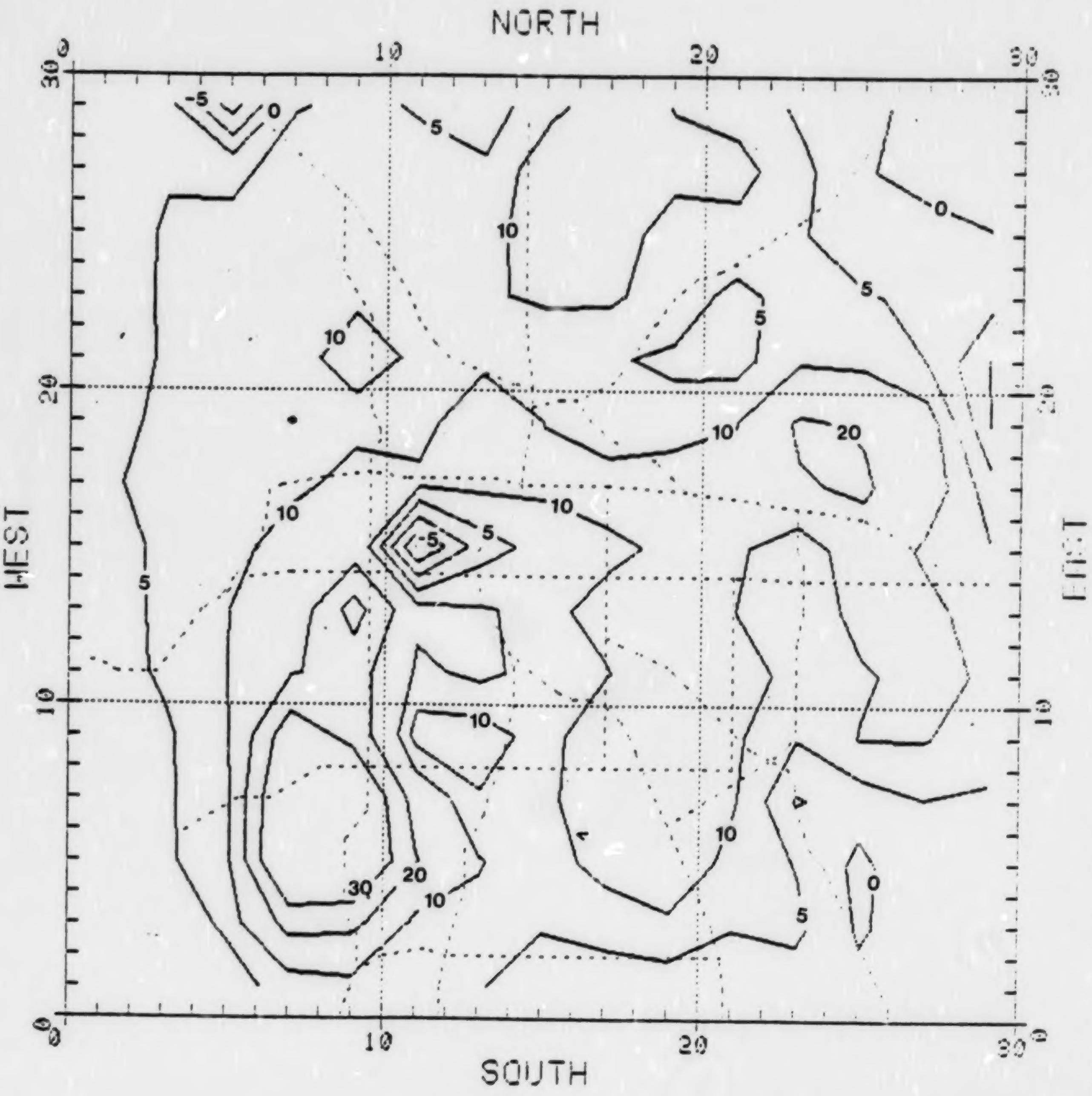
(a) 1974 to 1980

FIGURE III-10. INCREMENTAL CHANGES IN PARTICULATE CONCENTRATIONS PREDICTED BY CDM. Particulate concentrations in $\mu g/m^3$


NORTH
SOUTH
WEST
EAST
0
10
20
30
30
20
10
0
20
10
5
5
0
0
-5
10
10
20
30
10
10
5
0
-10
-5
5
20
10

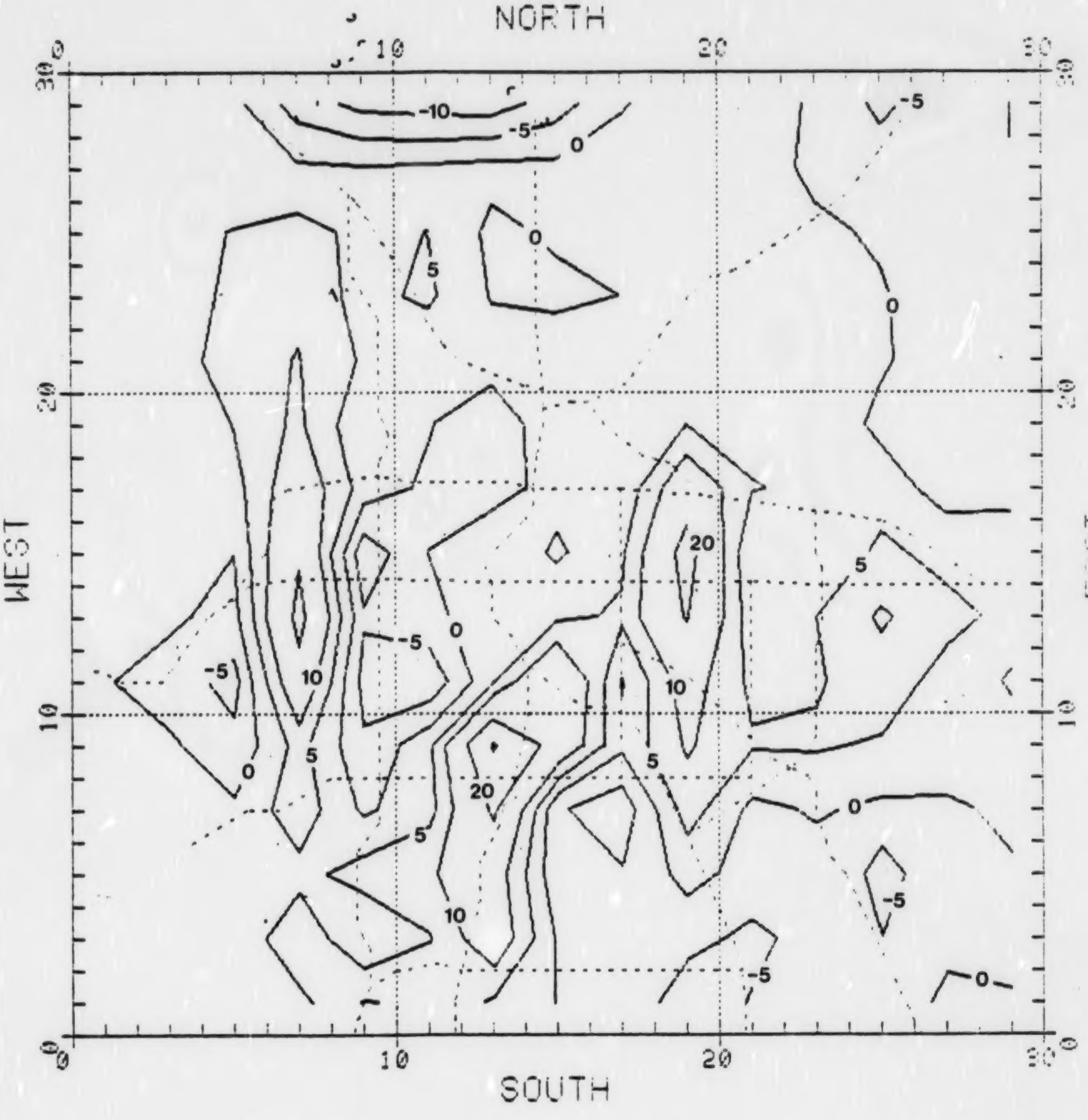
(b) 1980 to 1985

FIGURE III-10. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
-5
0
5
10
20
30

(c) 1985 to 1990

FIGURE III-10. (Continued)



(d) 1990 to 2000

FIGURE III-10. (Concluded)

2000, the largest increases are expected around the intersection of U.S. 285 and U.S. 85, and in the area south of Stapleton Airport. An area of increase is also predicted along State Route 391 in the vicinity of the Federal Center. Decreases are predicted in small areas to the north of Broomfield and in Douglas County Urban.

There is no consistent pattern to the incremental changes in NO_2 concentrations predicted by the CDM, although the increases between 1974 and 1980 correspond to the major highways to a large degree. The decrease predicted for downtown Denver between 1985 and 1990 might be an effect due to the changing character of the automobile population, which by 1990 should be meeting much more stringent NO_x emission controls.

Figure III-10 shows the incremental changes predicted by the CDM for particulate concentrations. The largest increases between 1974 and 1980 are expected in the area bounded by the freeways I-25, I-70, and I-270. Between 1980 and 1985 the maximum changes are predicted west of downtown, and some improvement is forecast along U.S. 285 south of Lowry AFB. Jeffco Urban has the largest increases in 1985 to 1990, while the area west of downtown improves slightly. Between 1990 and 2000, predicted concentrations increase in Lakewood and in the area of Lowry AFB, whereas decreases are forecast to the east and west of Lakewood.

The incremental changes predicted by CDM for particulates are not consistent from year to year. The increase in the urban portion of Jefferson County could be ascribed to the increase in construction activities required to accommodate the expected increase in population, but reference to Figure III-6 shows that this activity should be occurring in all years. It is hard to understand why particulate concentrations should decrease during any time period, since no general controls on particulates are expected. The reductions could occur because of the phasing out of some activity that generates large amounts of particulates, but more probably are an artifact of differences between the emissions inventories used.

D. CONCLUSIONS

The results of the base case studies of future air quality in the Denver region in relation to national and state air quality standards are summarized in Table III-3.

TABLE III-3. SUMMARY OF BASE CASE STUDIES AND AIR QUALITY STANDARDS

Pollutant	Averaging Period	Air Quality Standard		Observed Maximum (in year)	Predicted Concentration			
		Federal	Colorado		Model	1976	1985	2000
O_3	1 hour	0.08 ppm	--	0.18 ppm (1976)	Denver Model	0.24 ppm	0.13 ppm	0.09 ppm
CO	1 hour	35 ppm	--	51 ppm (1975)	Denver Model	26 ppm	17 ppm	4 ppm
	8 hour	9 ppm	--	24 ppm (1975)	Denver Model	15 ppm	10 ppm	3 ppm
NO_2	1 year	82 $\mu g/m^3$	--	79 $\mu g/m^3$ (1974)	Denver Model*	79$\mu g/m^3$	75$\mu g/m^3$	74$\mu g/m^3$
					CDM	79$\mu g/m^3$	97$\mu g/m^3$	94$\mu g/m^3$
					Rollback	79$\mu g/m^3$	105$\mu g/m^3$	114$\mu g/m^3$
Particulates	1 year	75$\mu g/m^3$	45$\mu g/m^3$	124$\mu g/m^3$ (1975)	CDM	168$\mu g/m^3$†	217$\mu g/m^3$	229$\mu g/m^3$

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*Predicted by ratio method--see text.

†For 1974 rather than 1976.

IV SENSITIVITY ANALYSIS

This chapter describes a study of the sensitivity of the air quality predictions presented in Chapter II to changes in input variables. Sensitivity analysis is a tool with which the response of a mathematical model to changes in input parameters and variables can be explored. Variables to which air quality predictions are sensitive fall into three main categories: those concerned with meteorological factors, those concerned with the air quality data used for input to the model, and those which affect the rate at which pollutants or pollutant precursors are emitted. We studied the effect of changes in variables in the first and third categories. We determined that calibrated CDM results depend directly on measured air quality, but DAQM ozone predictions for Denver are relatively insensitive to initial and boundary conditions determined from data (see Appendix A).

A. SENSITIVITY OF PREDICTIONS OF THE DENVER MODEL TO METEOROLOGICAL VARIABLES

The meteorological data input to the Denver Model, although defined over every grid square, are extrapolated from fairly sparse data. There are 24 wind stations taking hourly readings (although some data are missing). Each observation represents the air movement in the immediate vicinity of the monitor, whereas the model treatment assumes the observations are averages over an extensive area. The mixing depths used are inferred from the two temperature soundings per day and surface temperature measurements taken at Stapleton Airport. It is then assumed that these mixing depths are typical of the entire modeling region.

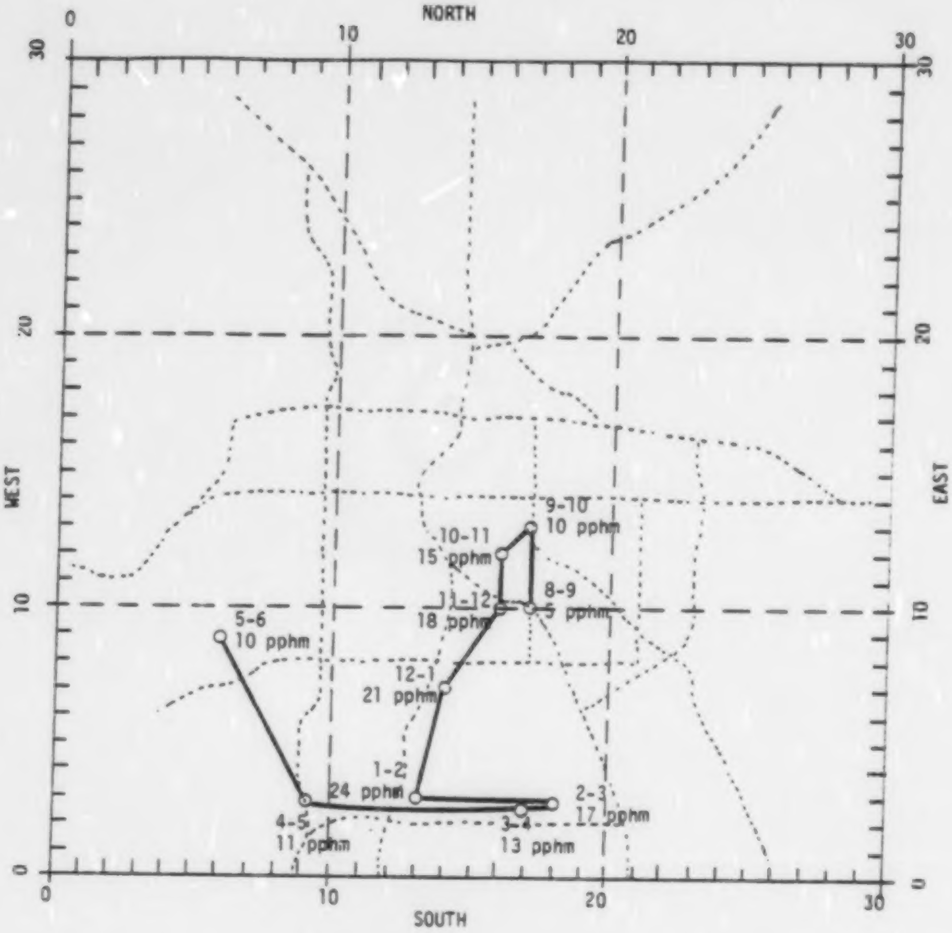
From the above description, it is evident that the meteorological data are by no means known with certainty. In addition, there is a form of uncertainty associated with the use of a particular day's meteorology to run the model. While this gives an element of realism in that on the days chosen ozone concentrations were high, the question arises as to what might happen if the meteorological conditions are worse on some occasion for which a prediction is required than they were on the days chosen? How high might the ozone concentration be?

In order to obtain a measure of the sensitivity of the predictions of the Denver Model to changes in meteorology, we ran three additional cases:

- Case 1--3 August 1976 meteorology with all wind speeds reduced by one-third.
- Case 2--3 August 1976 meteorology with the mixing depth reduced by one-third.
- Case 3--3 August 1976 meteorology with both wind speeds and mixing depth reduced by one-third.

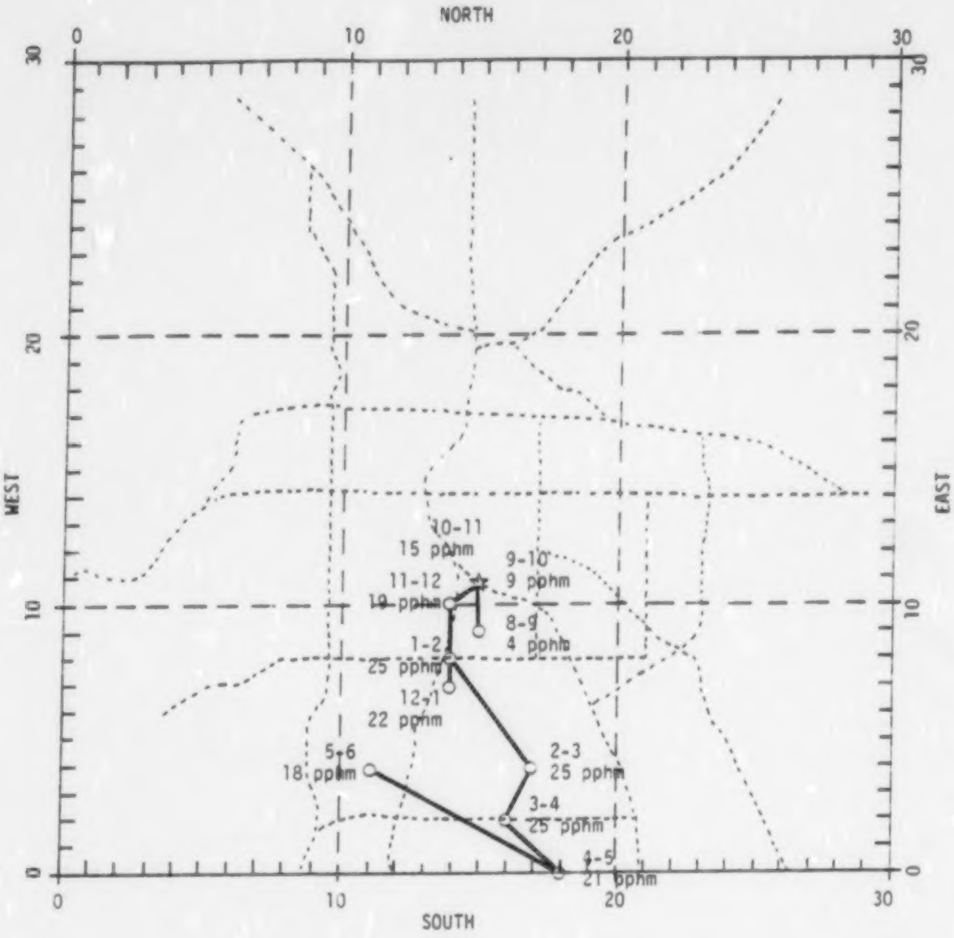
These three cases were compared with the 3 August 1976 base case to elucidate the dependence of the predictions of the Denver Model on wind speed and mixing depth, and to determine if their effects are compounded. The one-third reductions represent plausible variations within the uncertainty of a worst-case determination. In other words, the base case conditions represent our best estimate of the most adverse days of 1976, but we cannot exclude the possibility that one-third lower wind speeds or mixing depths might occur, with attendant higher ozone concentrations.

Details of the predictions of the Denver Model for 3 August 1976, one of the base case days, are presented in Chapter III. On that day, predicted ozone concentrations rose steadily to a peak one-hour-average concentration of 24 pphm, observed between 1 and 2 p.m. in the (42,32) grid cell. The approximate trajectory of the ozone cloud, as shown by the locations of successive one-hour-average ozone concentration maxima, is presented in Figure IV-1a. It may be seen that the concentration maxima


NORTH
0
10
20
30
WEST
EAST
SOUTH
9-10
10 pphm
10-11
15 pphm
11-12
18 pphm
8-9
5 pphm
5-6
10 pphm
12-1
21 pphm
1-2
24 pphm
2-3
17 pphm
4-5
11 pphm
3-4
13 pphm

(a) Meteorology of 3 August 1976

FIGURE IV-1. LOCATIONS AND VALUES OF PREDICTED MAXIMUM ONE-HOUR-AVERAGE OZONE CONCENTRATIONS FOR EACH HOUR FROM 8 a.m. TO 6 p.m.


NORTH
0
10
20
30
30
20
10
0
WEST
EAST
10-11
15 pphm
9-10
9 pphm
11-12
10 pphm
8-9
4 pphm
1-2
25 pphm
12-1
22 pphm
5-6
18 pphm
2-3
25 pphm
3-4
25 pphm
4-5
21 pphm
0
10
20
30
SOUTH

(b) Meteorology of 3 August 1976 with all wind speeds reduced by one-third

FIGURE IV-1. (Concluded)

are in the center of the region early in the day, are in the south and register the highest values in the early afternoon, and are in the southwest in the late afternoon.

Figure IV-1b shows a similar trajectory for Case 1, in which the wind speeds were reduced by one-third. The locations of the maximum concentrations of the entire day for the two cases are only about 3 miles apart, although the distances between hourly trajectory increments are much shorter for Case 1. The highest concentration observed for Case 1 was 25 pphm, and this concentration was observed for three consecutive hours.

The trajectory for Case 2 was similar to that of the base case, and that for Case 3 was similar to Case 1.

The maximum ozone concentrations predicted for each one-hour interval throughout the day are presented in Figure IV-2. The differences between different cases are small until about 11 a.m. Reducing the mixing depth had no effect on the time at which the peak predicted concentration was reached, but reducing the wind speed in both Cases 1 and 3 retarded the attainment of the peak by one hour. This effect is possibly ascribable to the slower movement of the air parcel under the influence of lighter winds, so that it remains longer in an area of high pollutant emissions. Thus a greater load of pollutants enters the parcel, with a concomitant increase in reaction time.

The maximum predicted ozone concentrations are higher for each case of more severe meteorological conditions. Recall that the base case resulted in a maximum concentration of 24 pphm. Reducing wind speed by one-third (Case 1) increased the predicted maximum to 25 pphm, an increase of 4 percent. Reduction of the mixing depth (Case 2) had a larger effect, increasing the maximum to 28 pphm, a 16 percent increase. When both conditions were combined (Case 3), the maximum predicted concentration

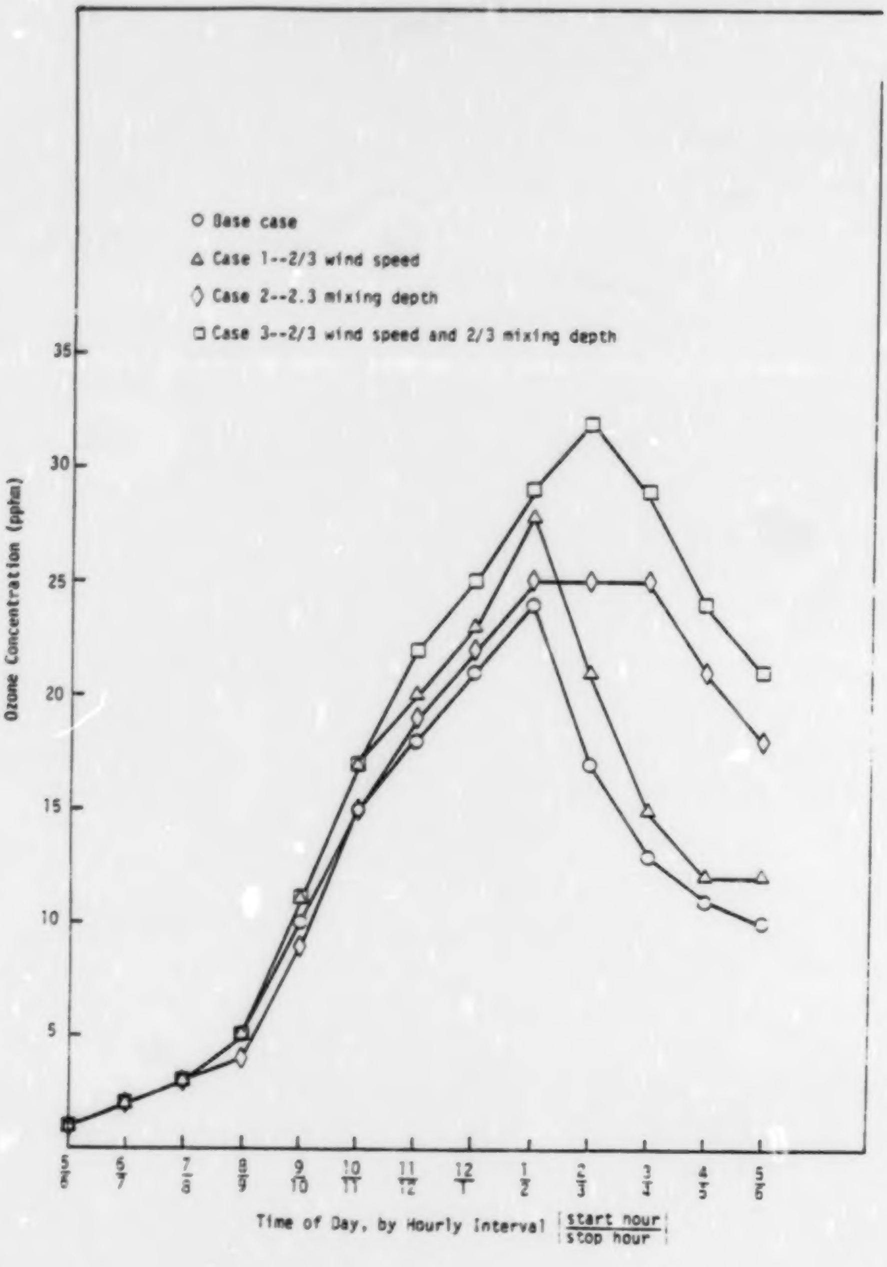


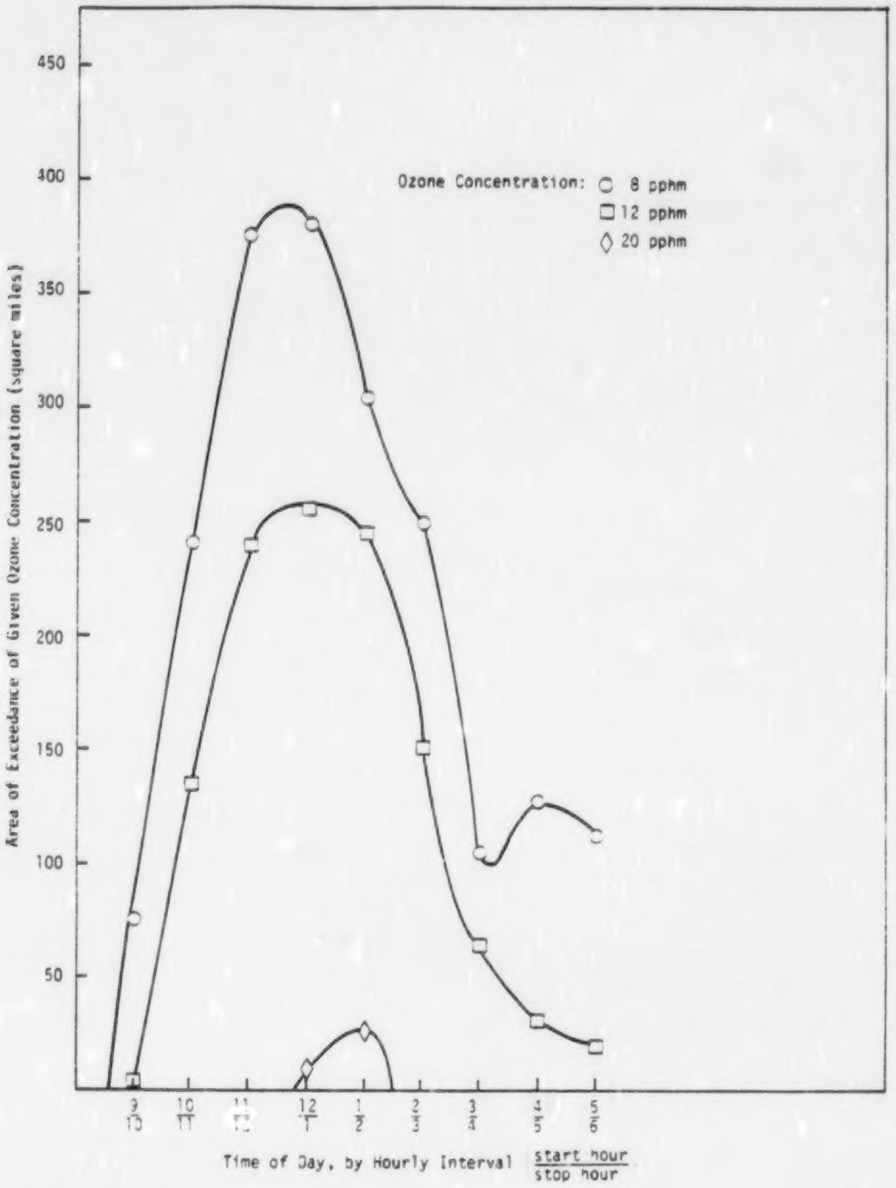
FIGURE IV-2. MAXIMUM ONE-HOUR-AVERAGE OZONE CONCENTRATIONS PREDICTED BY THE DENVER MODEL FOR VARIOUS CASES. 3 August 1976 meteorology assumed.

increased to 32 pphm, a 33 percent increase. Case 3 has considerably more effect than the sum of Cases 1 and 2, indicating some synergism. One might expect the effects to be multiplicative, since regional concentration is inversely proportional to wind speed and mixing depth according to simple box model analyses (e.g., Hanna, 1971). In the Denver Model results, the effect of Case 1 is less than 10 percent of that suggested by a box model analysis, and the effect of Case 2 is one-third of that suggested by a box model analysis. The combined effect (Case 3) is approximately one-fourth of the box model prediction of a $100[(3/2)^2 - 1] = 125$ percent increase in ozone concentration.

Another important measure of air quality in the region is the degree to which the NAAQS is violated. Figure IV-3 shows the number of square miles over which the NAAQS (8 pphm one-hour-average ozone concentration) is violated according to the predictions of the Denver Model for the base case and Cases 1, 2, and 3. Also shown are the numbers of square miles in which 10 pphm, 20 pphm, and 30 pphm one-hour-average ozone concentrations are exceeded. In all cases, the NAAQS is exceeded during the 9 to 10 a.m. period and this exceedance persists throughout the day. However, the maximum area of exceedance is about 380 square miles in the base case, but nearly 490 square miles in Case 3. Comparison of Figures IV-3a and IV-3c shows that a thinner mixing layer does not result in substantially greater exceedance areas. However, the areas having concentrations greater than 10 and 20 pphm are somewhat greater. Reducing the wind speed (Case 1) resulted in substantially greater areas of exceedance than the base case for all concentration levels. Again, as for the maximum concentrations reached, there is a synergism between Case 1 and Case 2 that results in their combined effect (Case 3) being greater than simply additive, but less than multiplicative.

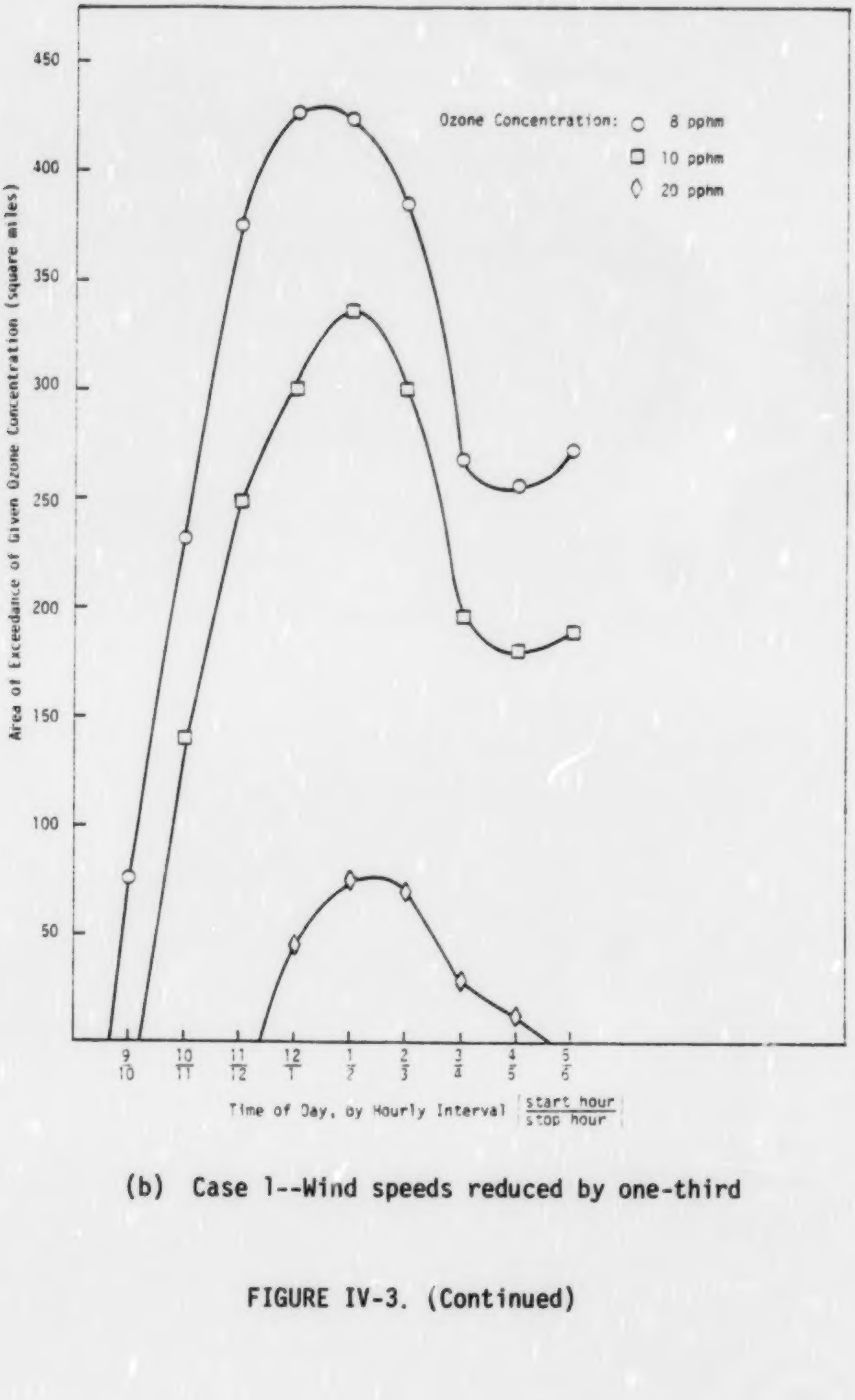
B. SENSITIVITY OF PREDICTIONS OF THE DENVER MODEL AND CDM TO THE SPATIAL DISTRIBUTION OF EMISSIONS

The base case studies for future years used projected emissions inventories (described in Appendix B), which were supplied by various



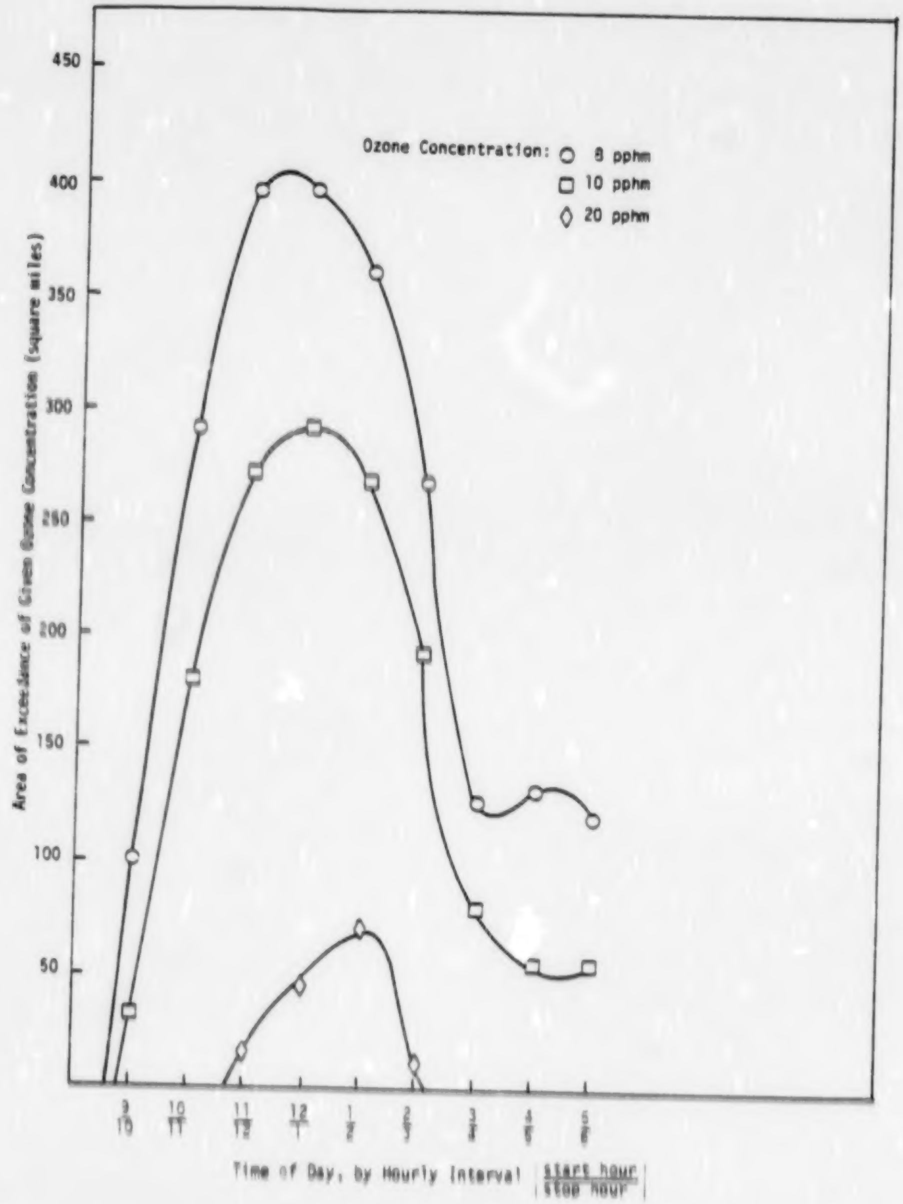
(a) Base Case

FIGURE IV-3. AREA OF EXCEEDANCE OF GIVEN OZONE CONCENTRATION FROM PREDICTIONS OF DENVER MODEL, FOR VARIOUS CASES. 3 August 1976 meteorology assumed.



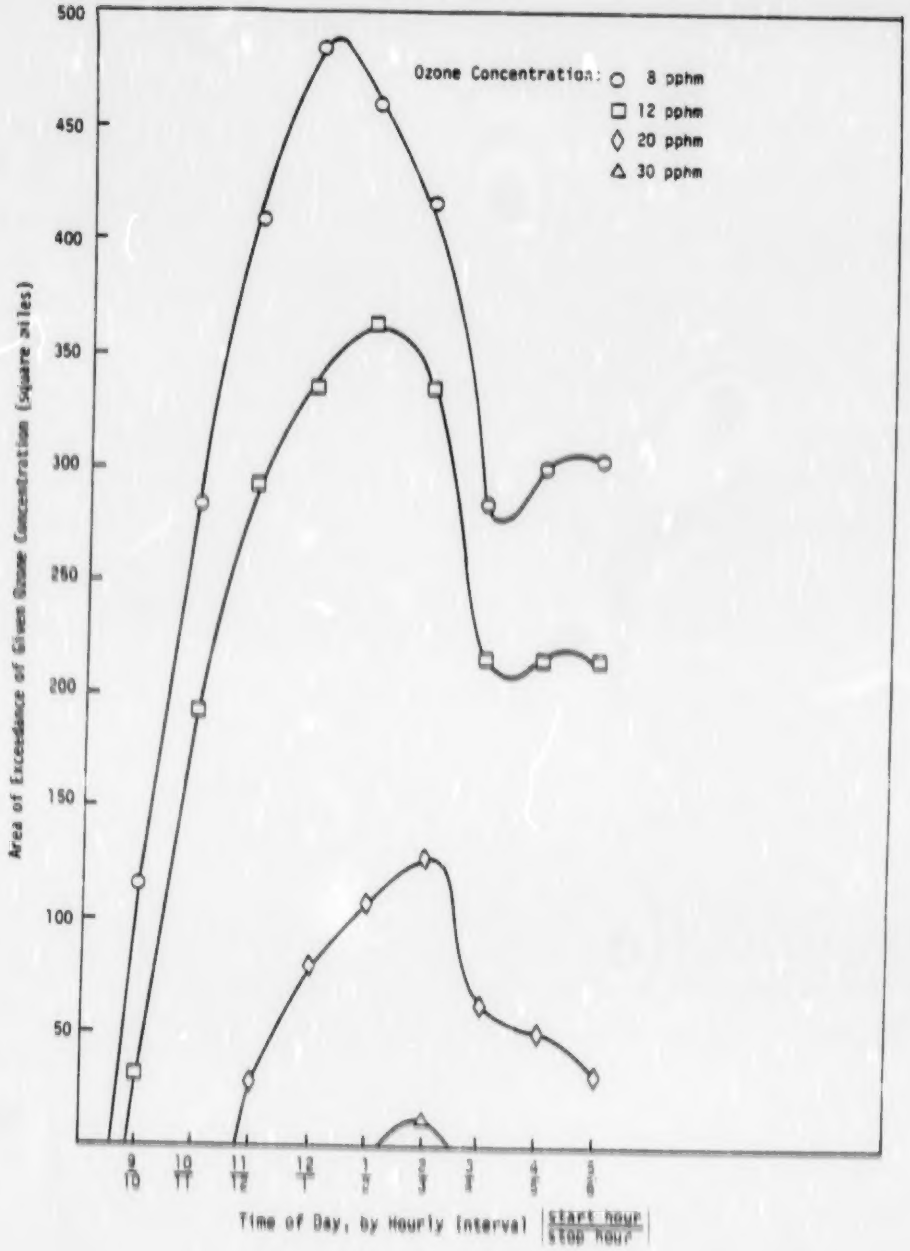
(b) Case 1--Wind speeds reduced by one-third

FIGURE IV-3. (Continued)



(c) Case 2--Mixing depth reduced by one-third

FIGURE IV-3. (Continued)



(d) Case 3--Wind speeds and mixing depth reduced by one-third

FIGURE IV-3. (Concluded)

public agencies. These inventories as supplied embody certain assumptions regarding future events. In particular, assumptions about the distribution of population growth through the year 2000 are included. In this section we describe our effort to ascertain the sensitivity of the air quality predictions to population growth patterns. This is not a study of alternative growth projections, only of whether growth patterns may be at issue, in terms of air quality projections.

Since we did not have access to the computer programs necessary to exactly reproduce the effects of different population distributions on emissions, we proceeded by making uniform percentage changes to all emissions within a study area, and comparing the results with a base case.

The base case chosen for study was the year 2000 with emissions inventories supplied by the Colorado Division of Highways and the Colorado Department of Health. These inventories are based on the following scenario:

> JRPP Highway Plan.
> Rail rapid transit system in operation (73 miles in 2000).
> Improved bus system (925 extra buses).
> Federal Motor Vehicle Control Program, as embodied in AP-42 (Supplement 5), installed and fully effective.
> DRCOG-approved population growth and allocation.

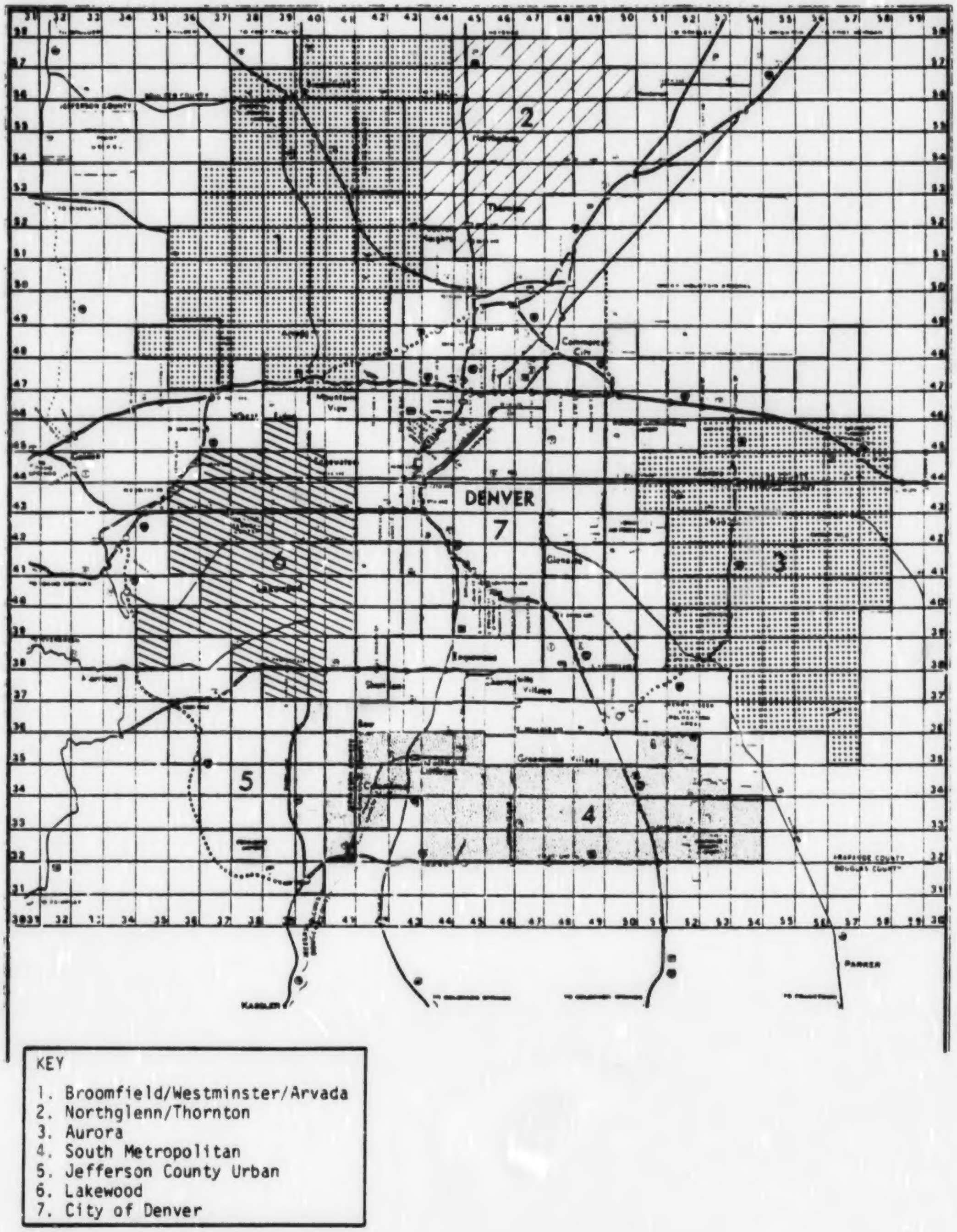
Certain areas were considered by the DRCOG to be subject to relatively high growth rates (see Appendix C, Figure C-22). From these we designated six suburban areas for study. Table IV-1 lists projected population increases for the areas chosen for study and Figure IV-4 shows their locations within the Denver region. These areas were chosen because they are distributed around the region and contain fast-growing communities. Assessment of the effect of changing emissions rates in these areas around the Denver metropolitan region will enable the elucidation of any special meteorological-geographical effects on air quality. We also changed emissions rates within the Denver city limits to estimate the potential effect of zero growth in activities there.

TABLE IV-1. POPULATION INCREASES PROJECTED FOR AREAS AROUND DENVER

No.	Area	Direction from Denver	Projected Population Increase (1975-2000)
1	Broomfield/Westminster/Arvada	NW	92,000
2	Northglenn/Thornton	N	45,000
3	Aurora	E	107,000
4	South Metro	S	57,200
5	Jeffco Urban	SW	116,700
6	Lakewood	W	90,600
7	City of Denver	--	114,400

To simulate a redistribution of population in different parts of the Denver region, we made computer runs in which the emissions rates in each of the first six areas described above were reduced by 25 percent, with emissions in all other areas increased in proportion to their emissions rates to maintain the same total emissions in the region. This procedure approximates reducing the population in an area by 25 percent while maintaining the same total population growth by redistributing it to other communities in proportion to their populations. An additional model run was made in which the emissions within the Denver city limits were reduced by 17.5 percent (the expected 1975-2000 population increase is only 17.5 percent) with redistribution as above.

We thus have the following eight runs for the sensitivity analysis:


DENVER
1
2
3
4
5
6
7
Commerce City
Thornton
Mountain View
Lakewood
Glendale
Englewood
Greenwood Village
Parker
Kassler
Arapahoe County
Douglas County

KEY

1. Broomfield/Westminster/Arvada
2. Northglenn/Thornton
3. Aurora
4. South Metropolitan
5. Jefferson County Urban
6. Lakewood
7. City of Denver

FIGURE IV-4. SUBREGIONS SELECTED FOR SENSITIVITY ANALYSIS

1. Base case: year 2000 emissions (28 July 1976 meteorology used in calculating ozone concentrations)
2. Emissions in Broomfield/Westminster/Arvada reduced 25 percent.
3. Emissions in Northglenn/Thornton reduced 25 percent.
4. Emissions in Aurora reduced 25 percent.
5. Emissions in South Metro reduced 25 percent.
6. Emissions in Jefferson County Urban reduced 25 percent.
7. Emissions in Lakewood reduced 25 percent.
8. Emissions in Denver reduced 17.5 percent.

We used the Denver Model to evaluate ozone concentrations and the CDM to evaluate NO_2 and particulate concentrations. Reservations as to the appropriateness of CDM for NO_2 studies expressed in previous chapters were not judged to be important here, since only the effects of changes to the base case are of interest.

1. Denver Model

The meteorology chosen for the sensitivity study was that of 28 July 1976. For that date and 1976 emissions, the Denver Model predicted a region-wide maximum one-hour-average ozone concentration of 20 pphm between 3 and 4 p.m. For the emissions inventory for the year 2000 and the same meteorology, the Denver Model predicted a maximum one-hour-average of 10 pphm between 2 and 3 p.m. For the seven sensitivity runs listed above, no difference was found in either the location, time, or magnitude of this maximum. In fact, the differences between the eight runs in terms of predicted ozone concentrations were confined at all times of day to at most a difference of 1 pphm in one or two grid squares.

Concentration differences should depend on the location of the emissions reduction area with respect to the region-wide emissions patterns for any given mean wind direction. The maximum changes were too small, however, to identify any such effect. In other words, all seven perturbations of the base case emissions inventory resulted in essentially identical region-wide predictions for ozone concentrations. This result is ascribed to the time factor in ozone production: by the time that significant amounts of ozone have been formed, the emissions are too well mixed to reflect their origins. Furthermore, the region-wide emissions were not changed in this exercise and in spite of the rather drastic imposition of growth control that the emissions changes would imply, no more than 7 percent of the region-wide emissions were redistributed. Thus, it is apparent that these changes in the spatial distribution of emissions have no effect on ozone concentrations. From this one may infer that land use controls that would reduce an area's population by as much as 25 percent without changing the regional population would be ineffective in terms of reducing ozone concentrations.

The sensitivity of one-hour-average NO_2 concentrations predicted by the Denver Model to the above emissions changes was not extensively analyzed. We noted, however, that almost undetectable changes were produced by the emissions pattern changes. CO concentrations would be affected in each area of reduced emissions but street-scale effects, which produce CO peaks, are not treated in the Denver Model.

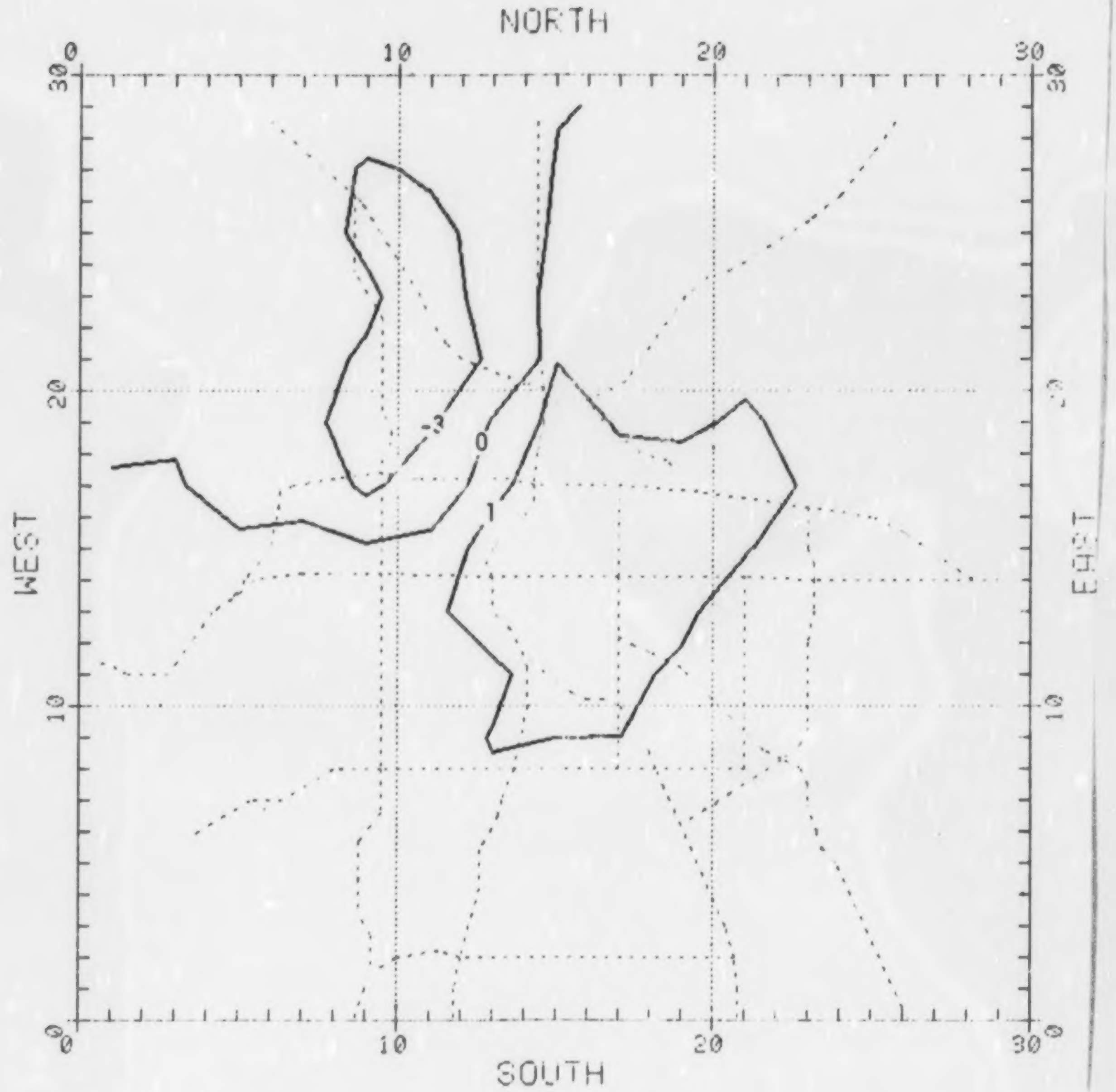
2. Climatological Dispersion Model (CDM)

CDM was used to evaluate annual average NO_2 and particulate concentrations for the eight cases listed above. As in the case of ozone concentrations, only slight differences in the calculated concentrations were noted in the immediate vicinity of each large perturbation in emissions. Table IV-2 lists the average concentrations and maximum concentrations predicted by CDM within each area for the base case and also for the case in which the total emissions in that area were reduced.

TABLE IV-2. EFFECTS OF CHANGES IN EMISSIONS ON PREDICTED AVERAGE AND MAXIMUM CONCENTRATIONS OF NO_2 AND PARTICULATES IN VARIOUS AREAS

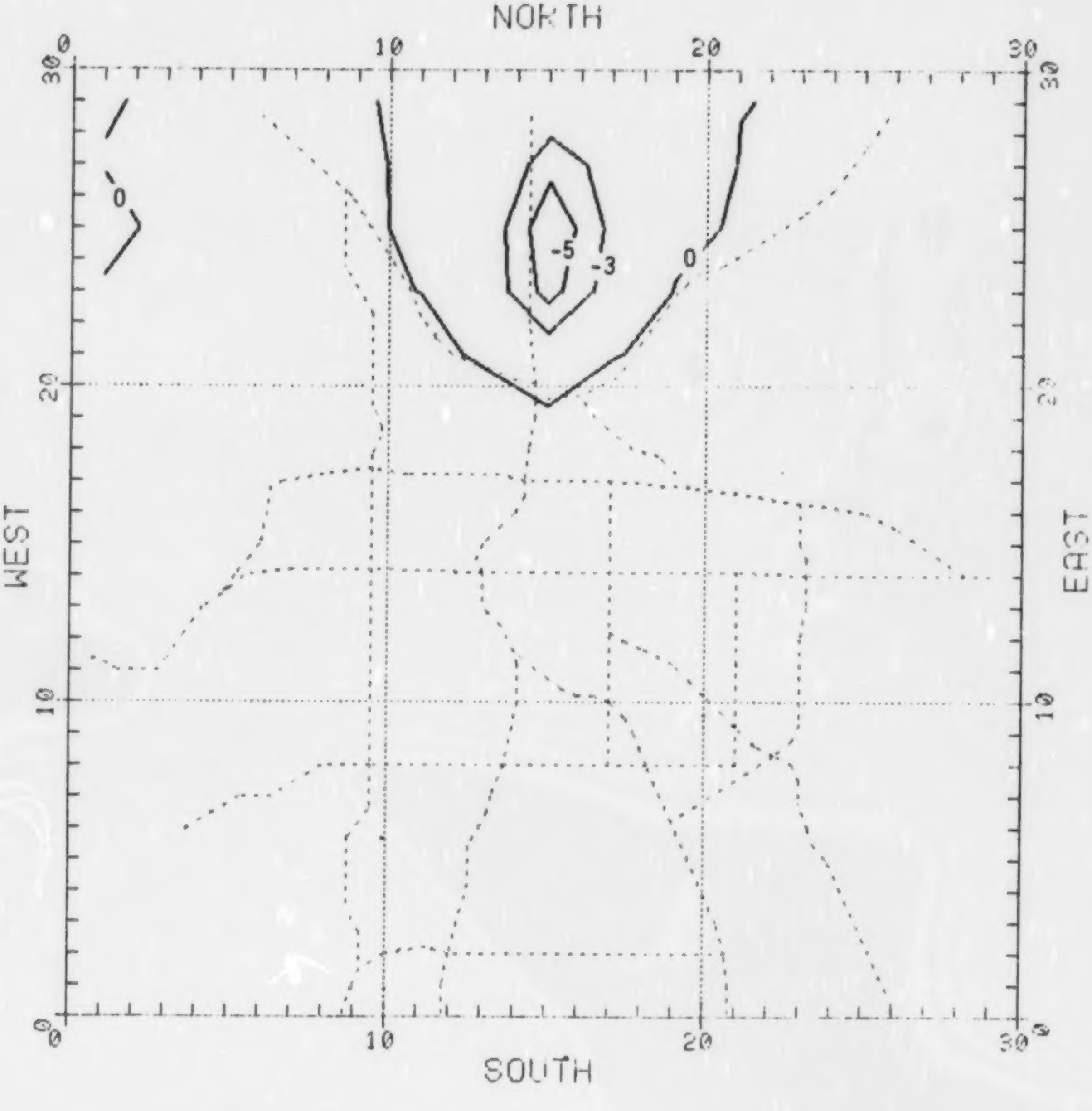
	Concentration ($\mu g/m^3$)							
	NO_2				Particulate			
	Base Case		Reduced		Base Case		Reduced	
Area	Avg	Max	Avg	Max	Avg	Max	Avg	Max
Broomfield/Westminster/ Arvada	32.6	59.1	29.8	56.5	118	161	112	160
Northglenn/Thornton	44.3	70.5	41.1	69.0	131	190	124	187
Aurora	22.1	53.9	19.7	50.9	101	123	95	116
South Metro	24.1	40.1	21.6	35.0	102	135	97	125
Jeffco Urban	23.6	31.2	20.9	28.1	126	159	114	139
Lakewood	38.4	56.3	34.0	52.9	140	173	130	159
Denver	60.0	94.1	54.2	83.5	164	229	153	206

Table IV-2 shows that a 25 percent reduction in emissions does not result in a 25 percent reduction in concentrations, but rather a 5-10 percent reduction only in the immediate area of the reduction in emissions. In order to ascertain whether the lowering of predicted concentrations was any more than a local effect, we calculated differences between the base case and each of the sensitivity runs in turn. These differences are presented as isopleths in Figures IV-5 and IV-6. These figures illustrate that the effect of large changes in emissions inventories remains localized rather than spreading region-wide. Most of the slight spreading that does occur is northward, which is reasonable in light of the annual wind rose calculated from the CDM data shown in Figure IV-7. This figure shows that almost 20 percent of the year the wind is from the south, and over 30 percent of the year it is from the south to southwest.


NORTH
SOUTH
WEST
EAST
0
10
20
30
-3
0
1

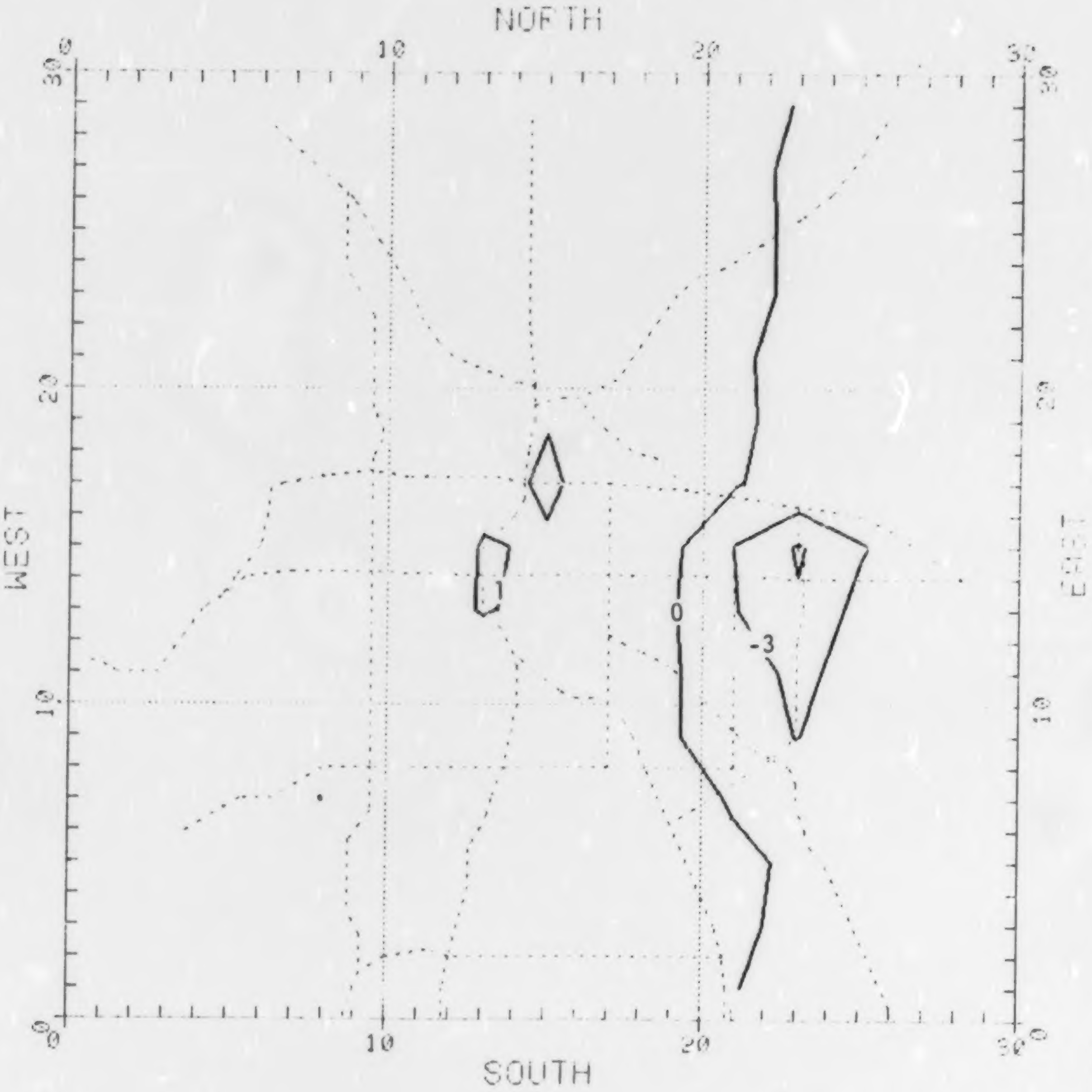
(a) Emissions Reduced by 25 Percent in Broomfield/Westminster/Arvada

FIGURE IV-5. ISOPLETHS (IN µg/m^3) OF DIFFERENCES BETWEEN ANNUAL AVERAGE NO_2 CONCENTRATIONS PREDICTED BY CDM FOR AN EMISSIONS REDUCTION IN A GIVEN AREA AND BASE CASE


NORTH
SOUTH
WEST
EAST
0
10
20
30
0
-5
-3
0

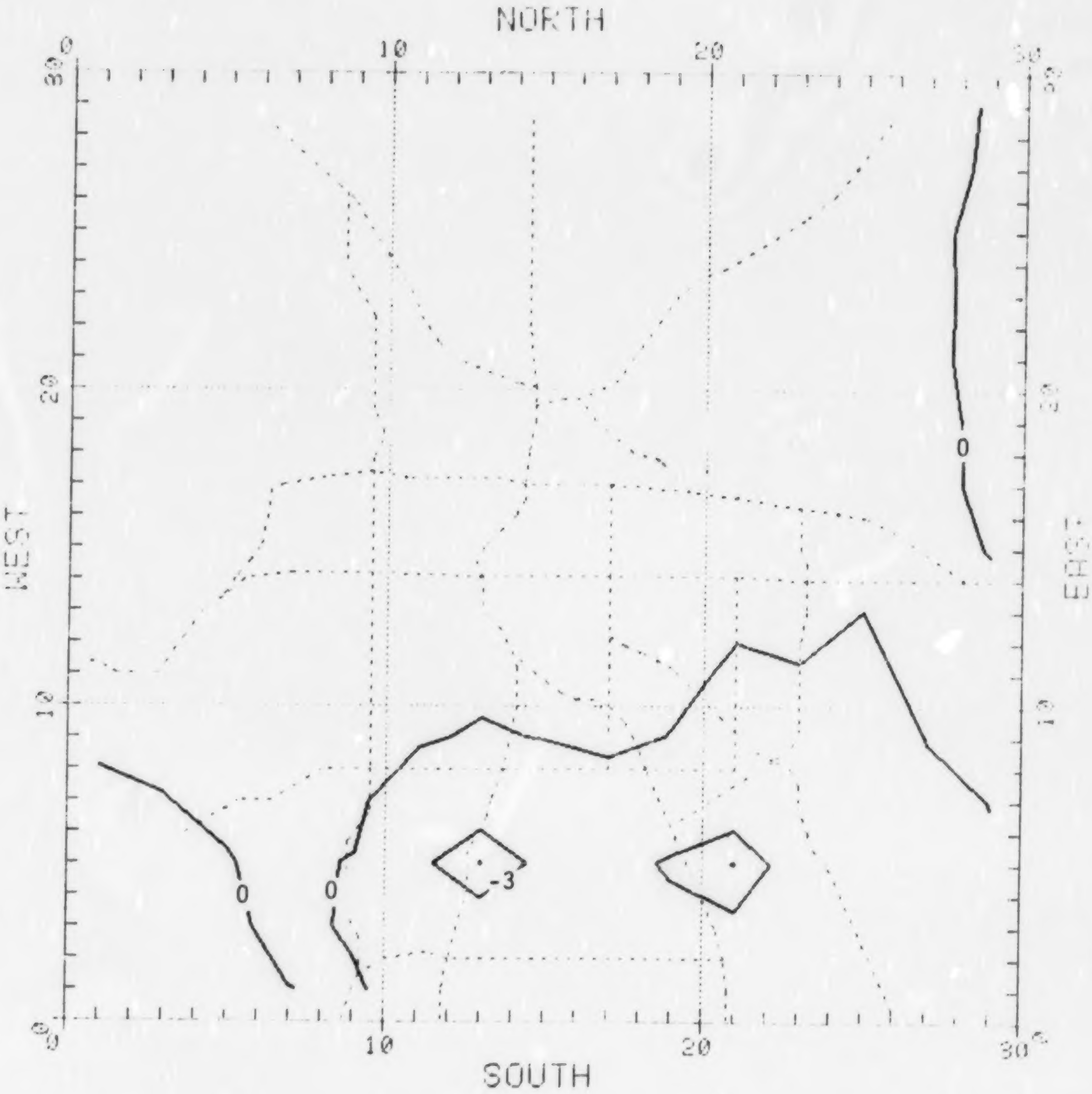
(b) Emissions Reduced by 25 Percent in Northglenn/Thornton

FIGURE IV-5. (Continued)



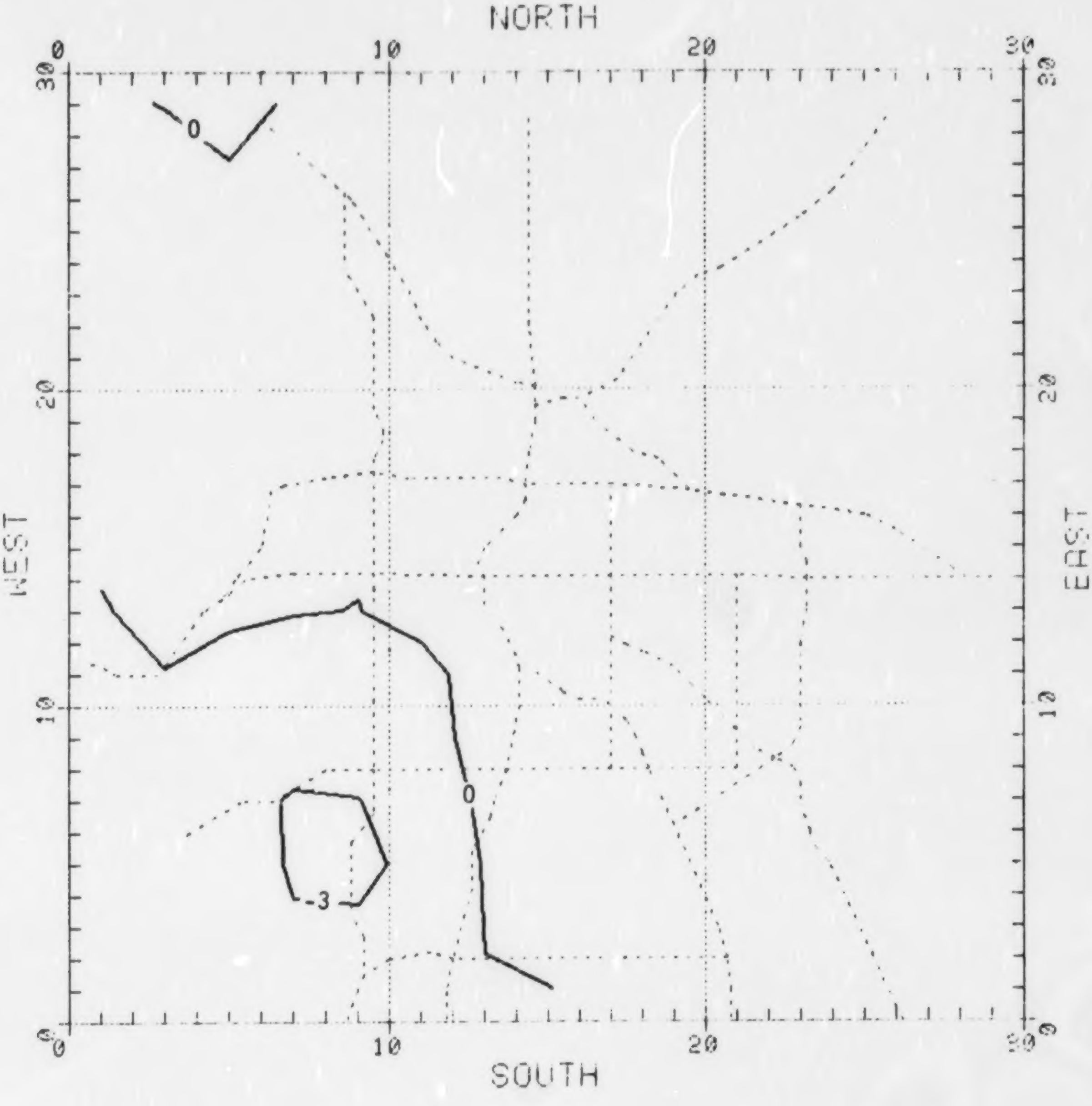
(c) Emissions Reduced by 25 Percent in Aurora

FIGURE IV-5. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
0
-3

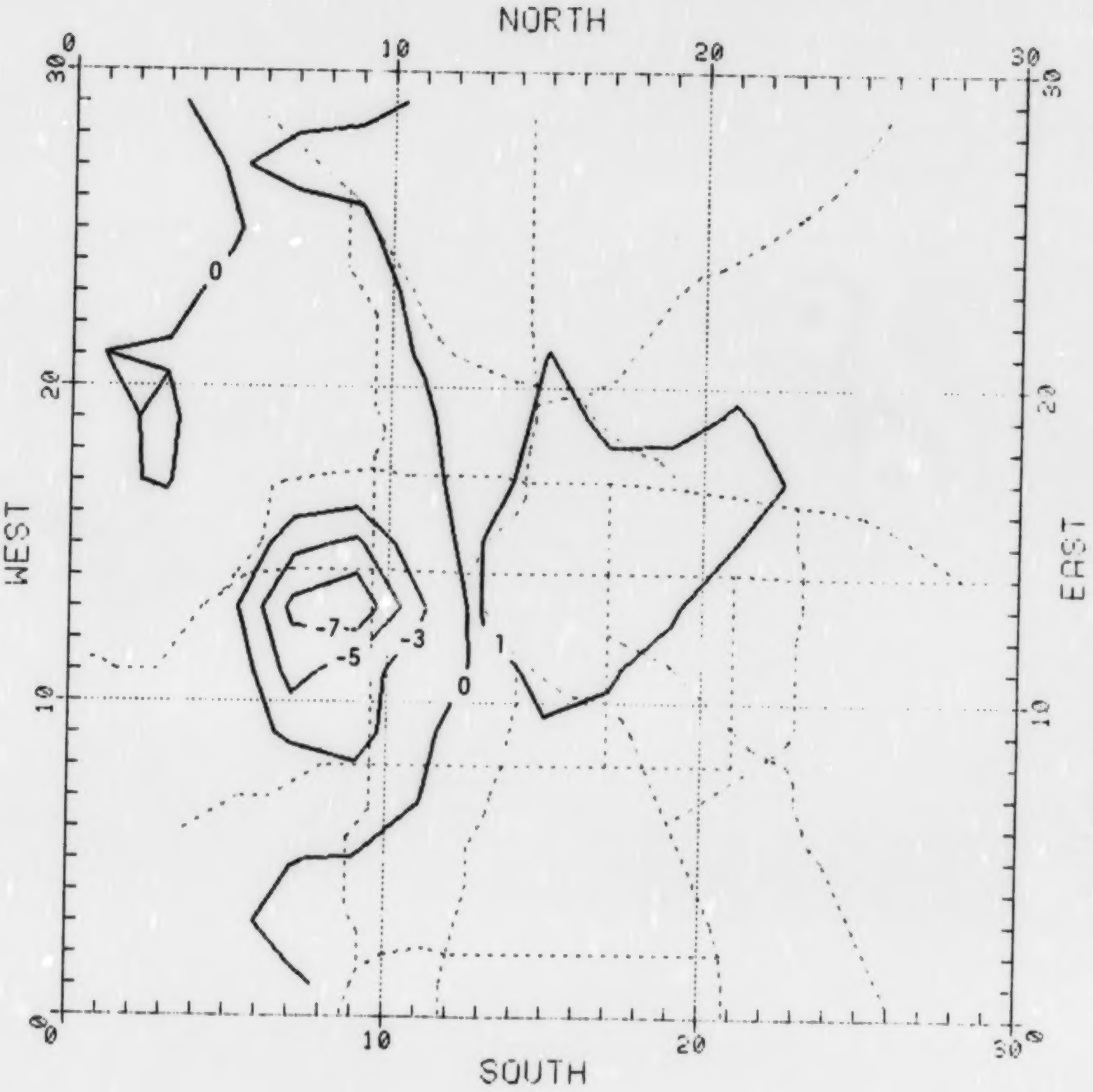
(d) Emissions Reduced by 25 Percent in Littleton/Arapahoe County Urban

FIGURE IV-5. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
0
-3

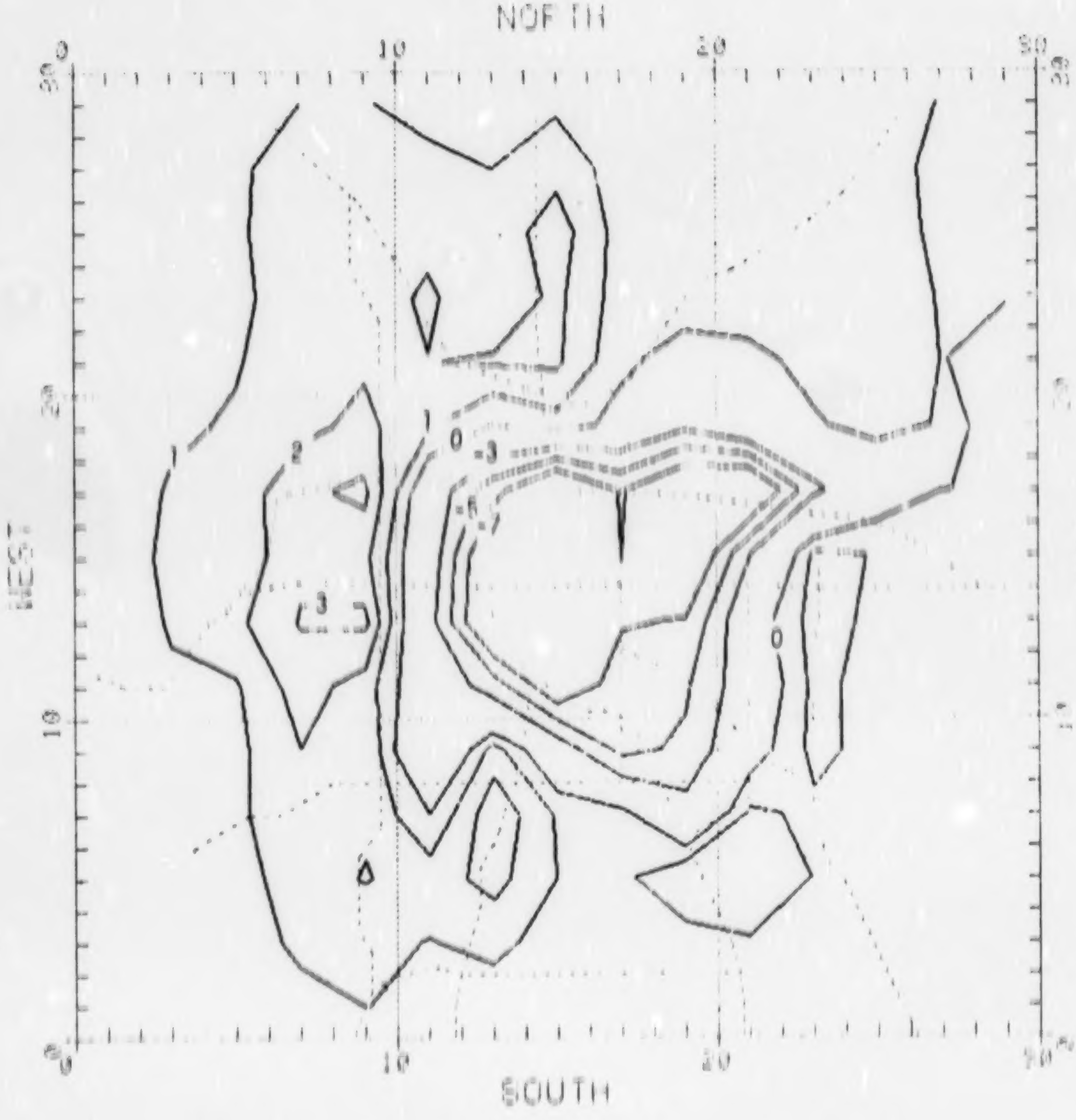
(e) Emissions Reduced by 25 Percent in
Jefferson County Urban

FIGURE IV-5. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
0
1
-3
-5
-7

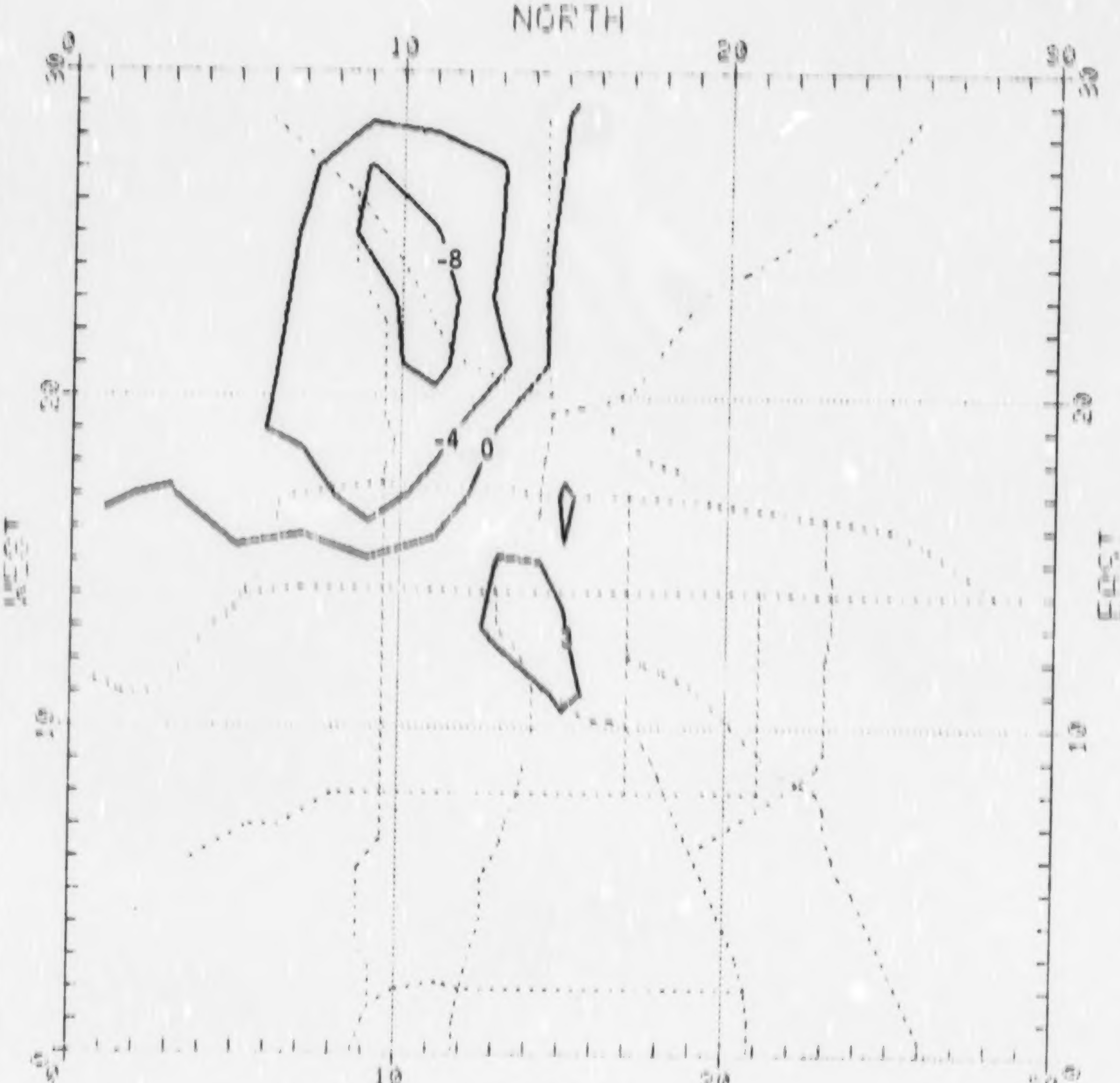
(f) Emissions Reduced by 25 Percent in Lakewood

FIGURE IV-5. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
1
2
3
0
-3
-5
-7
0

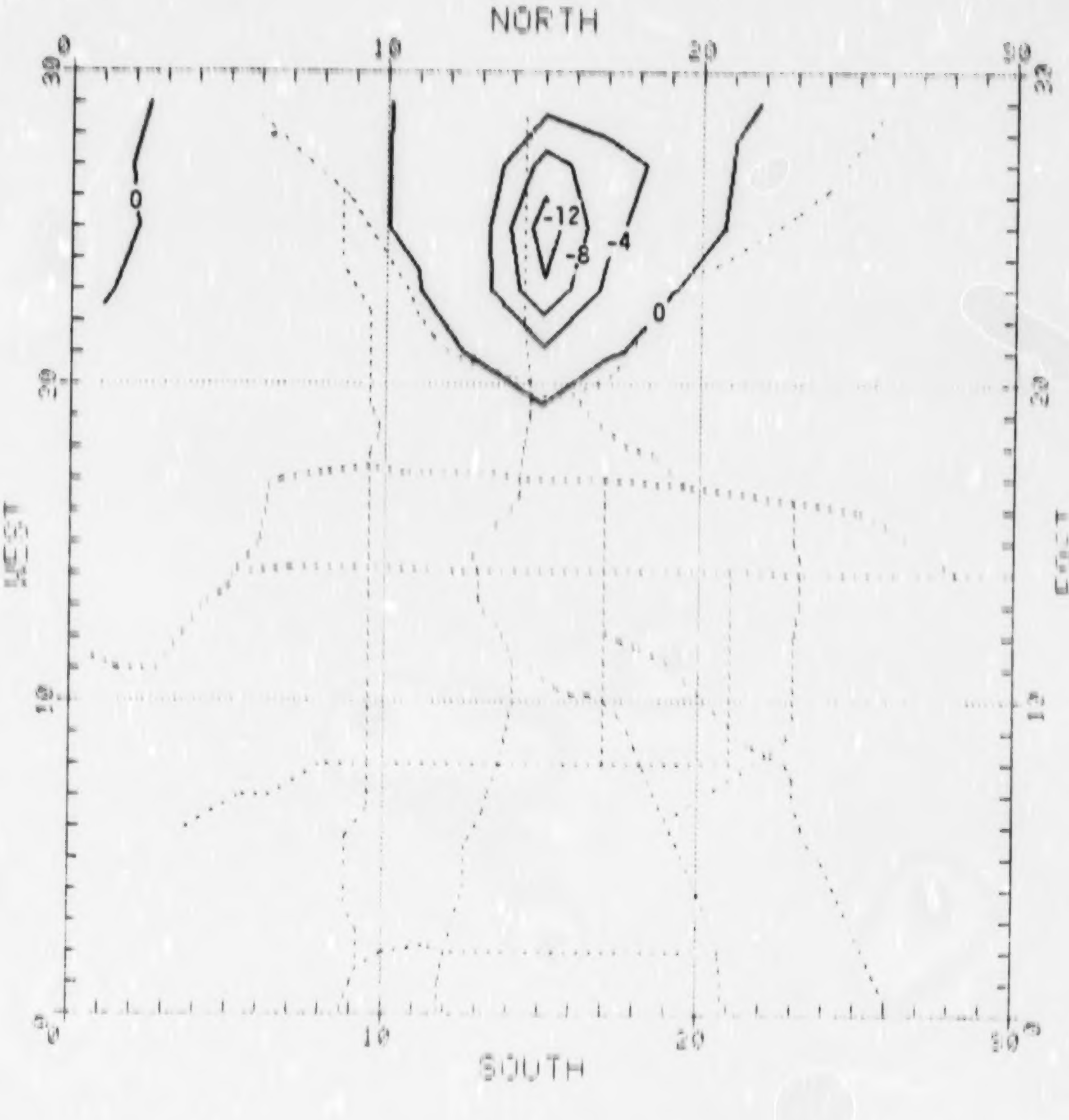
(g) Emissions Reduced by 17.5 Percent in City of Denver

FIGURE IV-5. (Concluded)


NORTH
SOUTH
WEST
EAST
0
10
20
30
-8
-4
0
3

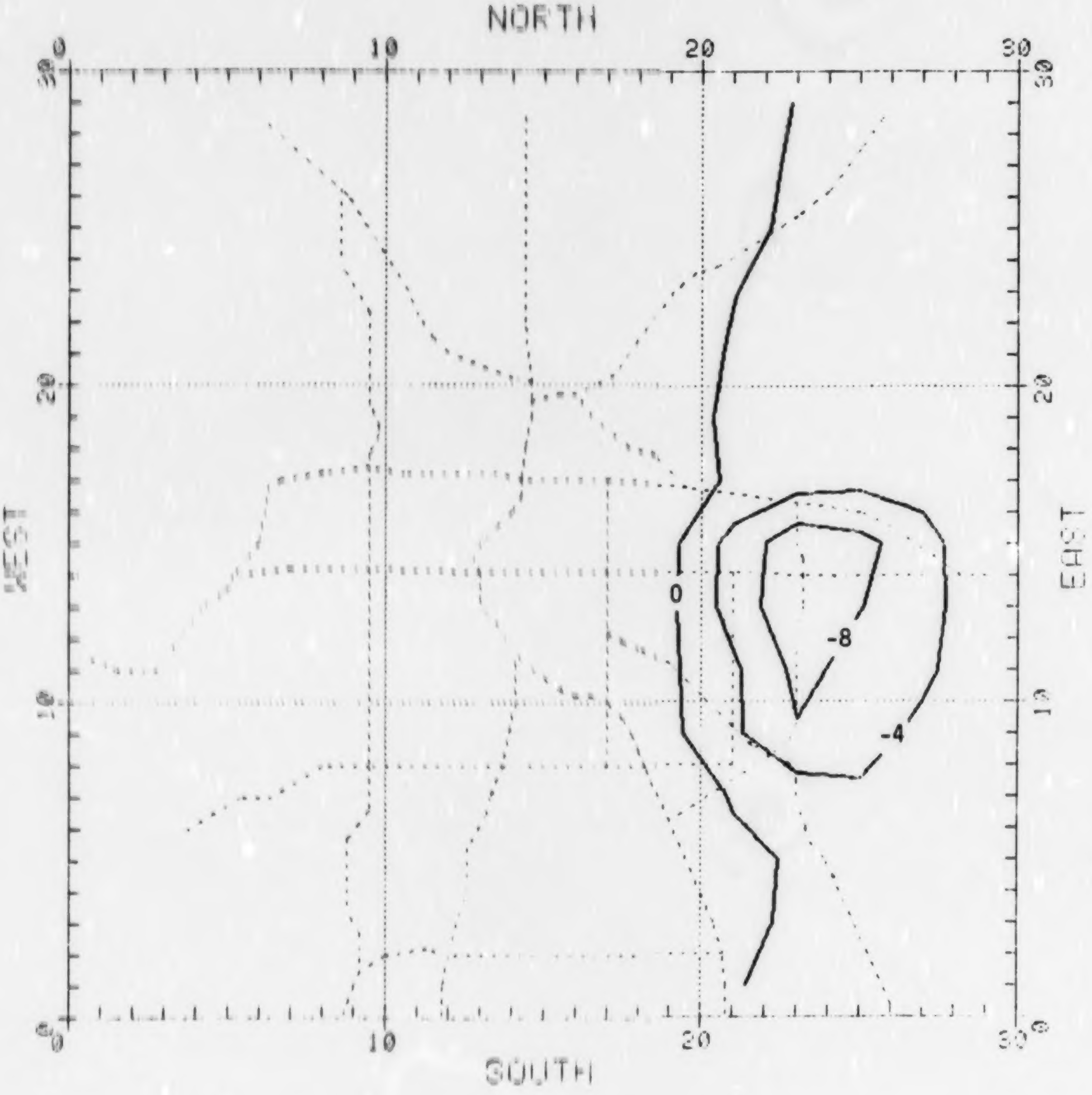
(a) Emissions Reduced by 25 Percent in Broomfield/Westminster/Arvada

FIGURE IV-6. ISOPLETHS (IN $\mu g/m^3$) OF DIFFERENCES BETWEEN ANNUAL AVERAGE PARTICULATE CONCENTRATIONS PREDICTED BY CDM FOR AN EMISSIONS REDUCTION IN A GIVEN AREA AND BASE CASE


NORTH
SOUTH
WEST
EAST
0
10
20
30
32
0
-12
-8
-4
0

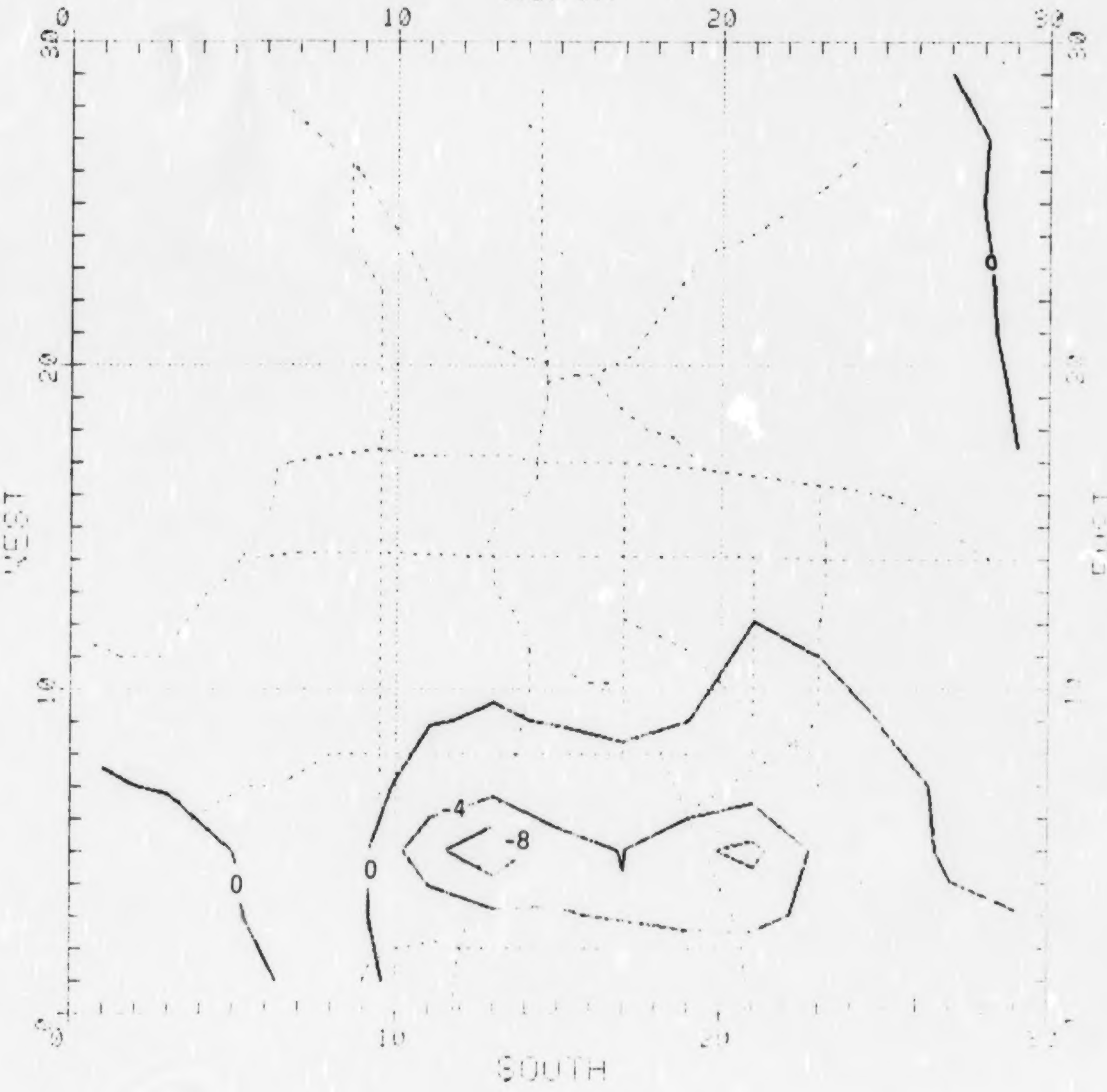
(b) Emissions Reduced by 25 Percent in Northglenn/Thornton

FIGURE IV-6. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
-8
-4

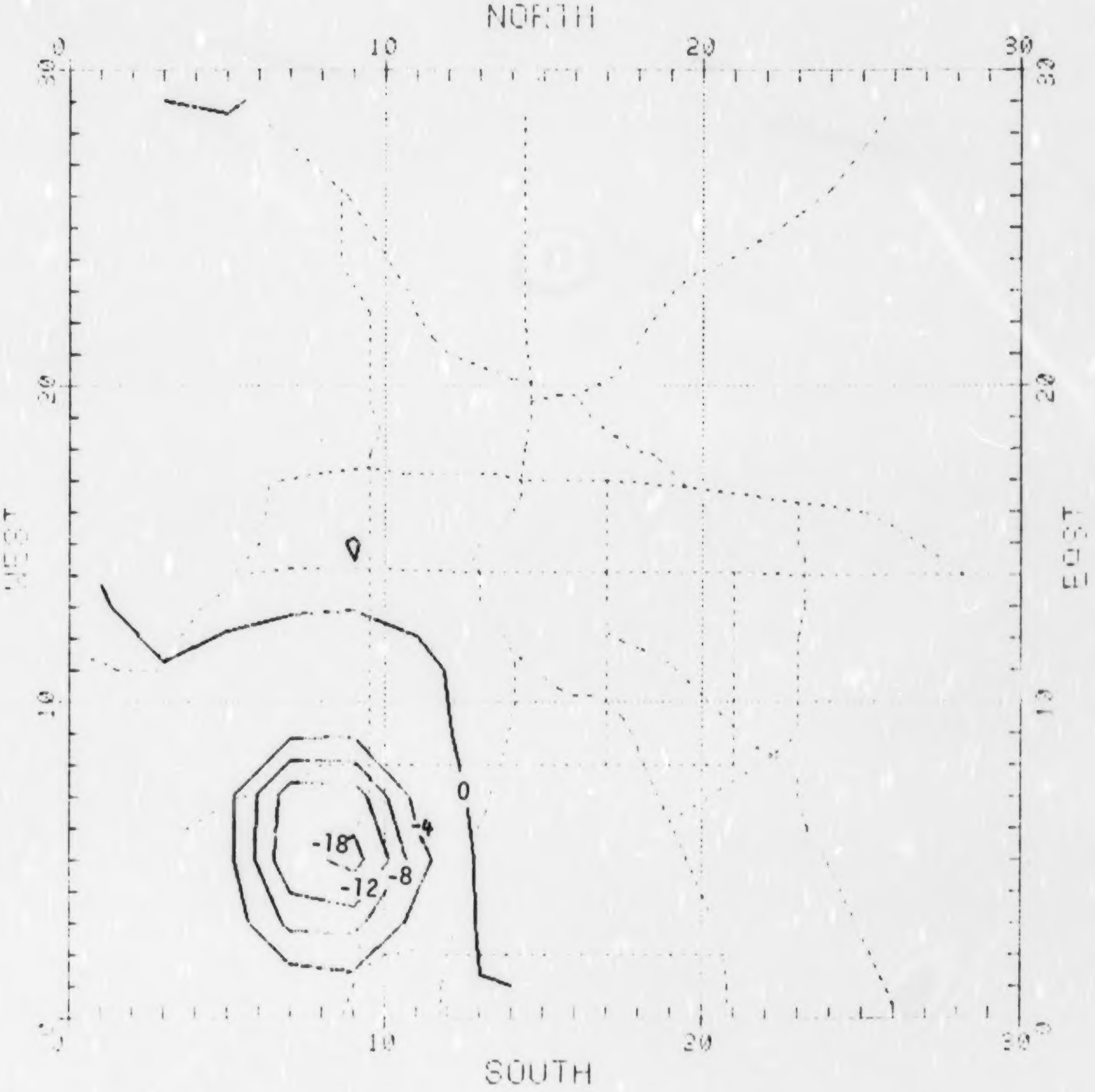
(c) Emissions Reduced by 25 Percent in Aurora

FIGURE IV-6. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
0
-4
-8

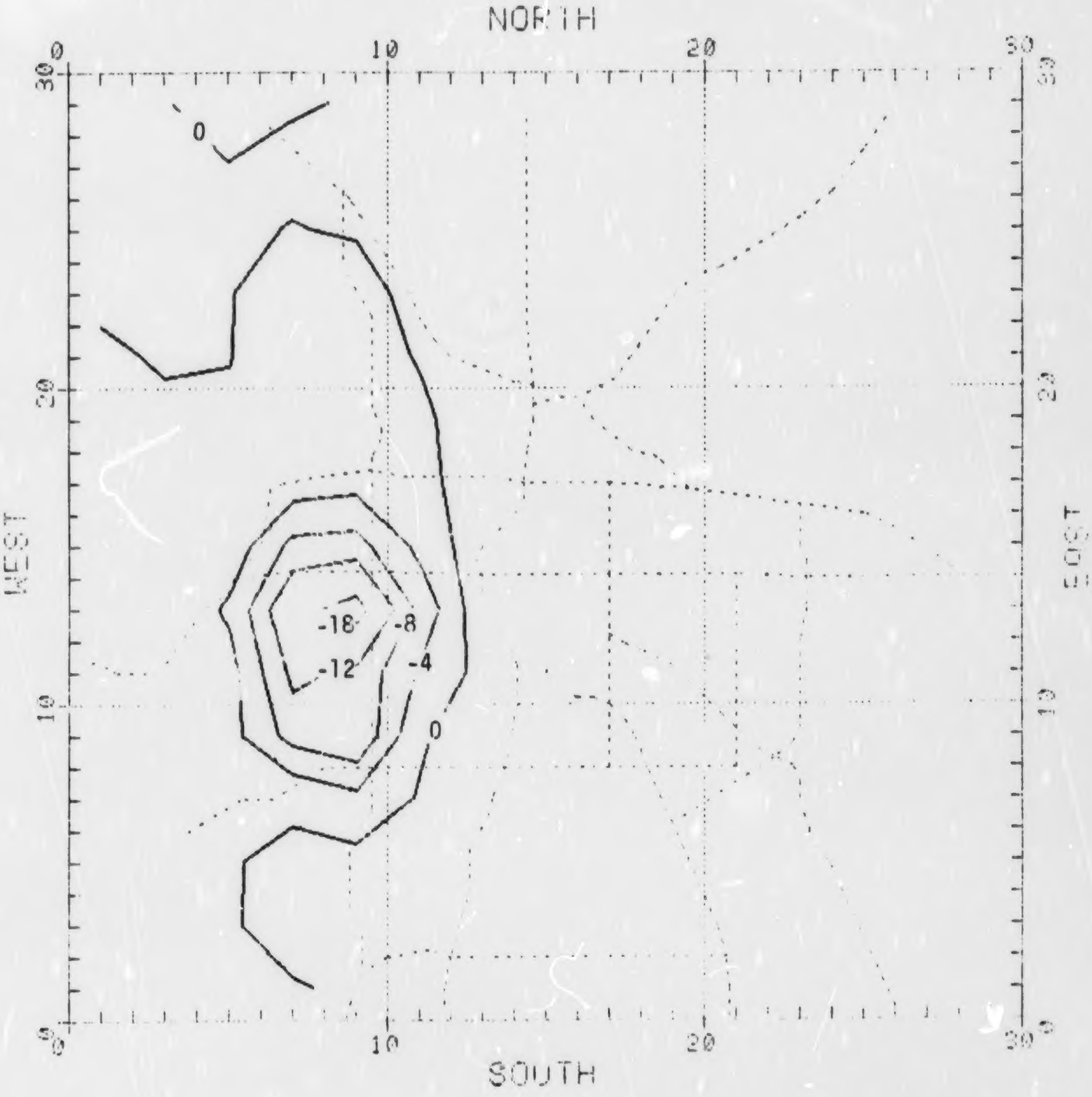
(d) Emissions Reduced by 25 Percent in Littleton/Arapahoe County Urban

FIGURE IV-6. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
0
-4
-8
-12
-18

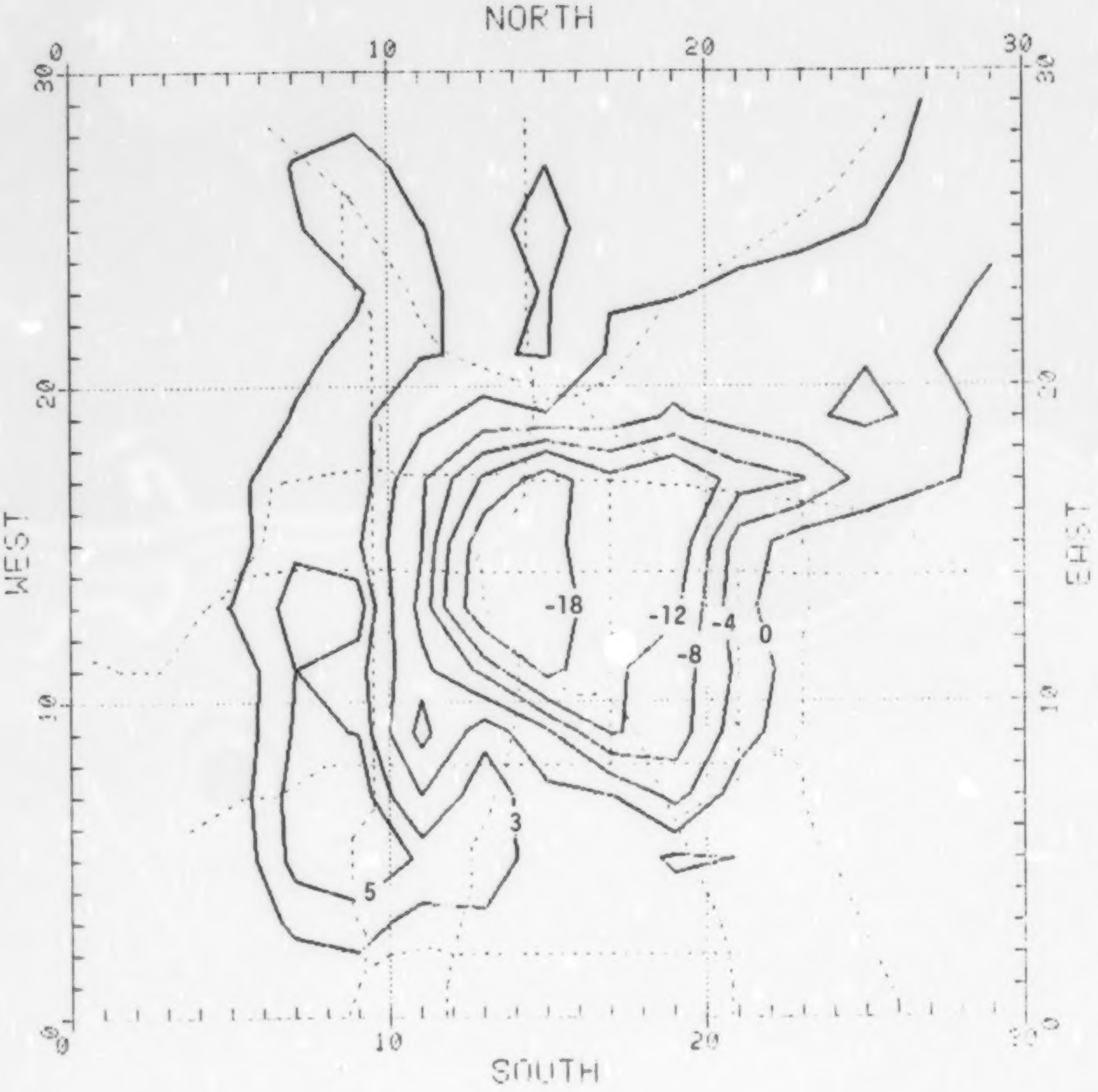
(e) Emissions Reduced by 25 Percent in Jefferson County Urban

FIGURE IV-6. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
0
-18
-12
-8
-4
0

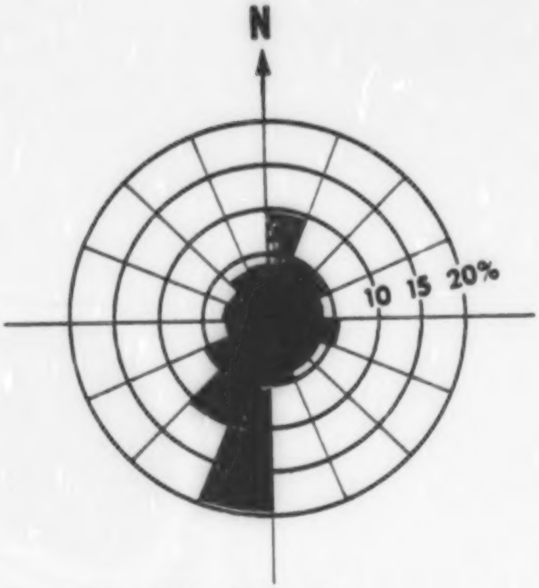
(f) Emissions Reduced by 25 Percent in Lakewood

FIGURE IV-6. (Continued)


NORTH
SOUTH
WEST
EAST
0
10
20
30
-18
-12
-8
-4
0
3
5

(g) Emissions Reduced by 17.5 Percent in City of Denver

FIGURE IV-6. (Concluded)



Source: 1971-1974 STAR data.

FIGURE IV-7. ANNUAL WIND ROSE FOR THE DENVER METROPOLITAN REGION

C. CONCLUSIONS

The main conclusion from the sensitivity study is that region-wide control of pollutant concentrations is not achievable by large-scale redistribution of emissions. For ozone, which is formed by reactions of emissions, it was found that perturbations in emissions rates of 25 percent in different communities had no effect on region-wide concentrations. For species subject to annual average standards, only local reductions in concentrations could be observed, and the fractional changes in concentrations were less than the fractional changes in emissions. Thus it would not be fruitful to require emissions reductions in small areas in order to relieve regional problems. It would seem that region-wide effectiveness will only be achieved through region-wide controls. Furthermore, local changes in emissions would have to be proportionally greater than the desired changes in local pollutant concentrations, since local concentrations depend to some extent on regional emissions.

V MITIGATION CONSIDERATIONS

The base case results described in Chapter III show substantial improvement in Denver's air quality between the present and the year 2000. Grid cell averages of peak ozone and CO concentrations are predicted by the Denver Model to decrease to the respective NAAQS or less. "Hot spot" violations of the NAAQS for CO are predicted to decrease in frequency, and NO_2 is expected to stay within the NAAQS. (Predicted annual-average NO_2 concentrations have large uncertainties, as discussed in Chapter III.) All of these predictions depend on certain assumptions, which may or may not prove to be valid. The most significant assumptions are that:

> Growth projections for the Denver region are accurate.
> Vehicle emissions will meet the standards of the Federal Vehicle Emissions Control Program (FVECP).

In this chapter we discuss the effects of these assumptions on predicted pollutant concentrations. We also briefly discuss the effects of some mitigation measures.

A. GROWTH PROJECTIONS

Errors in growth projections can be either positive or negative, although growth beyond projected levels would presumably require wastewater treatment facilities in excess of those presently proposed. On the other hand, a decision to not fund the proposed facilities would probably limit growth to less than projected levels. It seems likely, therefore, that Denver's growth will not greatly exceed projections, and considering this factor alone, future air quality is conservatively predicted by the base cases.

B. VEHICLE EMISSION FACTORS

To study the effects of assuming that the emissions factors specified in the Federal Vehicle Emissions Control Program (FVECP) would be met, particularly at Denver's altitude, we carried out simulations with the Denver Model using other emission factors. The sets of vehicle emission factors studied with the Denver Model are as follows:

- Set 1--the AP-42 emission factors. The EPA publication AP-42, Supplement 5, contains emission factors for an average mix of vehicles for future years. Thus AP-42 emission factors are based on the assumptions that (1) the emissions standards in the Federal Vehicle Emission Control Program (FVECP) will be met, and (2) the mix of vehicles of various ages, which are affected by different emission standards, will be as specified in that document.
- Set 2--emissions factors selected by the staff of EPA Region VIII to represent a vehicle fleet subject to emission regulations not as severe as those implied by AP-42. The degree of emission control with Set 2 emission factors was estimated to be in excess of that provided by presently proposed Colorado vehicle inspection and maintenance programs.
- Set 3--the emission factors of Set 1 with a higher Federal NO_x emission standard.
- Set 4--the emission factors of Set 2 with a higher Federal NO_x emission standard.

The distribution of ozone concentrations with Set 2 emission factors we similar to the results obtained with Set 1 factors that graphical presentations are not given here. (The results of simulations with Set 1 of emission factors are given in Chapter III.)

The significance of some changed emission factors on peak ozone concentrations may be seen in Figure V-1. In this figure peak ozone

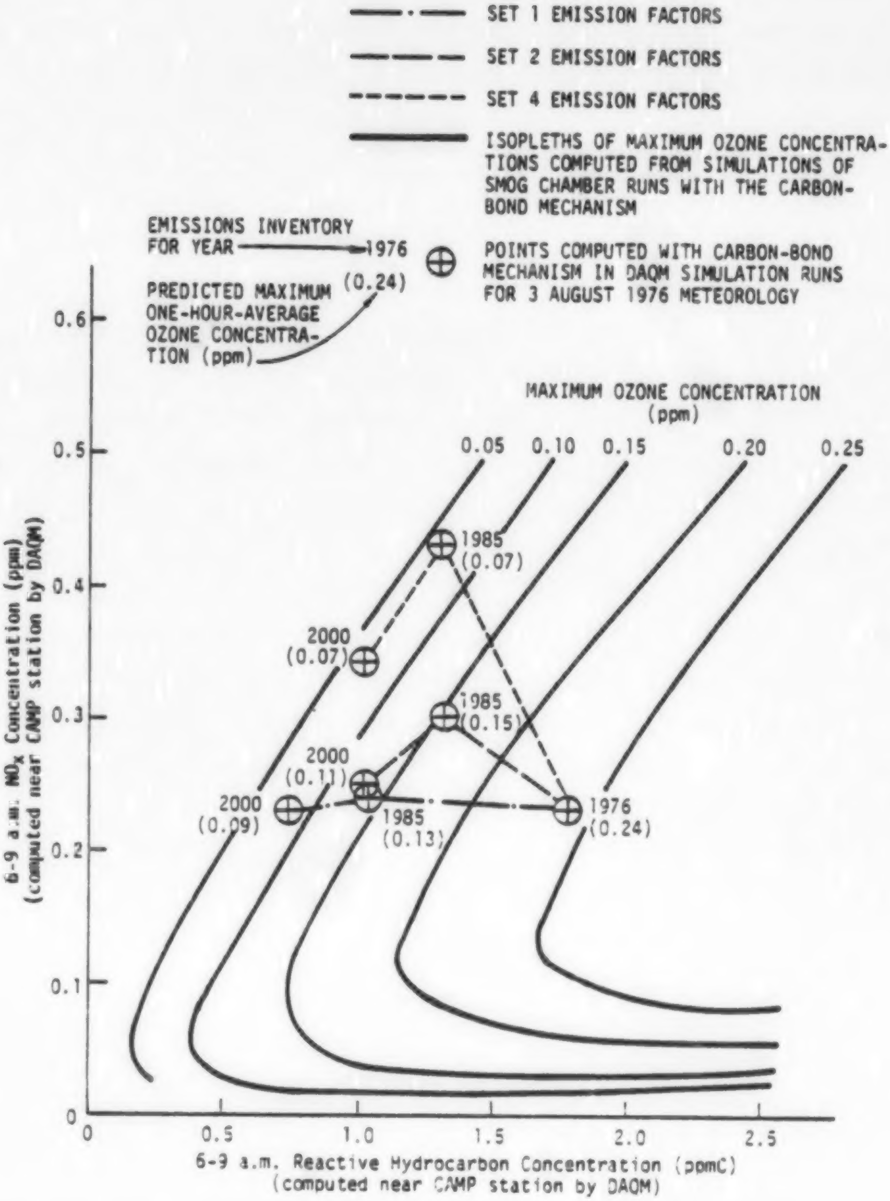


FIGURE V-1. MAXIMUM OZONE COMPUTED BY CARBON-BOND SIMULATIONS OF SMOG CHAMBER EXPERIMENTS AND BY DENVER MODEL FOR VARIOUS ASSUMED SETS OF FUTURE EMISSIONS

concentrations for 3 August 1976 are plotted as a function of precursor concentrations. Points are plotted for Set 1, Set 2, and Set 4 of emission factors. Set 2 leads to predicted ozone peaks about 2 pphm higher than Set 1. This increase is sufficient to infer clear, but small, NAAQS ozone violations in the year 2000. Set 2 also leads to more severe violations in 1985 than Set 1.

Set 3 of emission factors was found to lead to ozone concentrations that are substantially equivalent to those computed with Set 4 of emission factors. In either case, no violations of the NAAQS for ozone are predicted to occur in 1985. It is very important to note, however, that these conclusions apply only to ozone concentrations within the modeling region. Ozone concentrations outside the modeling region and NO_x concentrations within or without the region might well be adversely affected by relaxing the Federal standard for vehicular NO_x emissions.

Set 2 of emission factors also affected peak grid-cell-average CO concentrations. The winter simulations showed peak one-hour-average CO concentrations of 27 ppm in 1985 and 6 ppm in 2000. These figures are both below the NAAQS for CO of 35 ppm. The calculated eight-hour-average concentrations for Set 2 were 16 ppm in 1985 and 5 ppm in 2000. Thus violation of the NAAQS of 9 ppm CO is predicted for 1985 but not for 2000.

C. ADDITIONAL MITIGATION STUDIES

Given a population distribution, emissions may be affected by many mitigation measures, but of the measures proposed (see Appendix C), the most significant two (in addition to strict FVECP compliance, discussed above) were judged to be

- > Expansion of mass transit facilities
- > Hydrocarbon vapor recovery at gasoline delivery nozzles.

1. Mass Transit

Estimates of the effect of a proposed expansion of the Regional Transportation District (RTD) bus fleet by approximately 1000 buses were made. These estimates included consideration of anticipated ridership and use of private automobiles between home and bus stop. The latter consideration is especially important since by the year 2000 little improvement is anticipated in cold start emissions, but warm trip emissions are expected to decrease. The result of the study of RTD expansion was that a 1 percent effect on emissions would be most likely and that the effect is unlikely to exceed 2-1/2 percent. The reductions should be widely distributed and thus a smaller fractional change is expected in peak ozone concentrations for reasons discussed below.

2. Hydrocarbon Vapor Recovery

The effect of a Stage II vapor recovery system* was studied. We estimate that the effect of such a system would reduce Denver's peak ozone concentrations by no more than 1 pphm. The analysis follows.

The emissions inventory supplied to SAI by the Air Pollution Control Division of the Colorado Public Control Division of the Colorado Public Health Department showed about 5 percent of the hydrocarbons emitted into the regional atmosphere result from filling fuel tanks at gasoline stations. Mr. David Joseph of EPA Region VIII expressed reservations about this amount; he believes that gas station emissions might be as much as 50 percent higher.

The California Air Resources Board (Venturini and Grandy, 1975) estimates that uncontrolled gasoline stations emit about 0.0024 pounds of hydrocarbons per supplied vehicle mile traveled. Of this about 40 percent may be controlled by submerged fill pipes, so about 0.0014

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*Stage II vapor recovery provides for double hose or equivalent systems for recovery of hydrocarbon vapors at filling nozzles in gasoline stations.

(#HC/VMT supplied) would be ascribable to the vehicle tank filling operation. In 1973 in California these emissions represented about 11 percent of all stationary source HC emissions and about 5 percent of all HC emissions. These figures would confirm the reasonableness of 5 to 7 percent for Denver.

Several reports indicate the feasibility of 90 percent recovery of vapor emitted during vehicle tank filling operations (Venturini and Grandy, 1975; Radian Corporation, 1975; Scott Research Laboratories, 1974). This would suggest a potential reduction in present Denver total HC emissions of 5 to 6 percent. If anticipated reductions in all other categories of HC emissions are realized, the vapor recovery program would represent a 6 to 8 percent reduction of the 1985 emissions inventory and a 9 to 11 percent reduction of the year 2000 emissions inventory.

The photochemical simulation of a 30 percent reduction in all emissions reported later in this chapter indicates a fractional reduction in peak ozone concentrations of roughly one-half the fractional reduction in emissions. This would suggest that a reduction in ozone of about 3 percent in 1976, 4 percent in 1985 and 5 percent in 2000 could be achieved by Stage II vapor recovery. These numbers are clearly small compared to the accuracy of analyses, observations, or emissions forecasts. However, Stage II vapor recovery would not affect NO_x emissions. An estimate of ozone reduction at a constant NO_x level may be obtained from the ozone isopleth chart shown in Figure V-2. Here it is seen that the ozone gradient is about $(0.24-0.17)/(0.24-0.20) = 0.07/0.04 = 1.75$ times as great for a reduction from 1976 HC at constant NO_x as it is for a reduction in both NO_x and HC by the same percentage. Thus a decrease of about 1 pphm in peak ozone concentrations might be expected from immediate institution of a Stage II program.

Venturini and Grandy (1975) estimate the cost-effectiveness of a Stage II system to be about 15 to 50 cents per pound of HC controlled. This is compared with the cost-effectiveness of other proposed control techniques in Table V-1, taken from their paper.

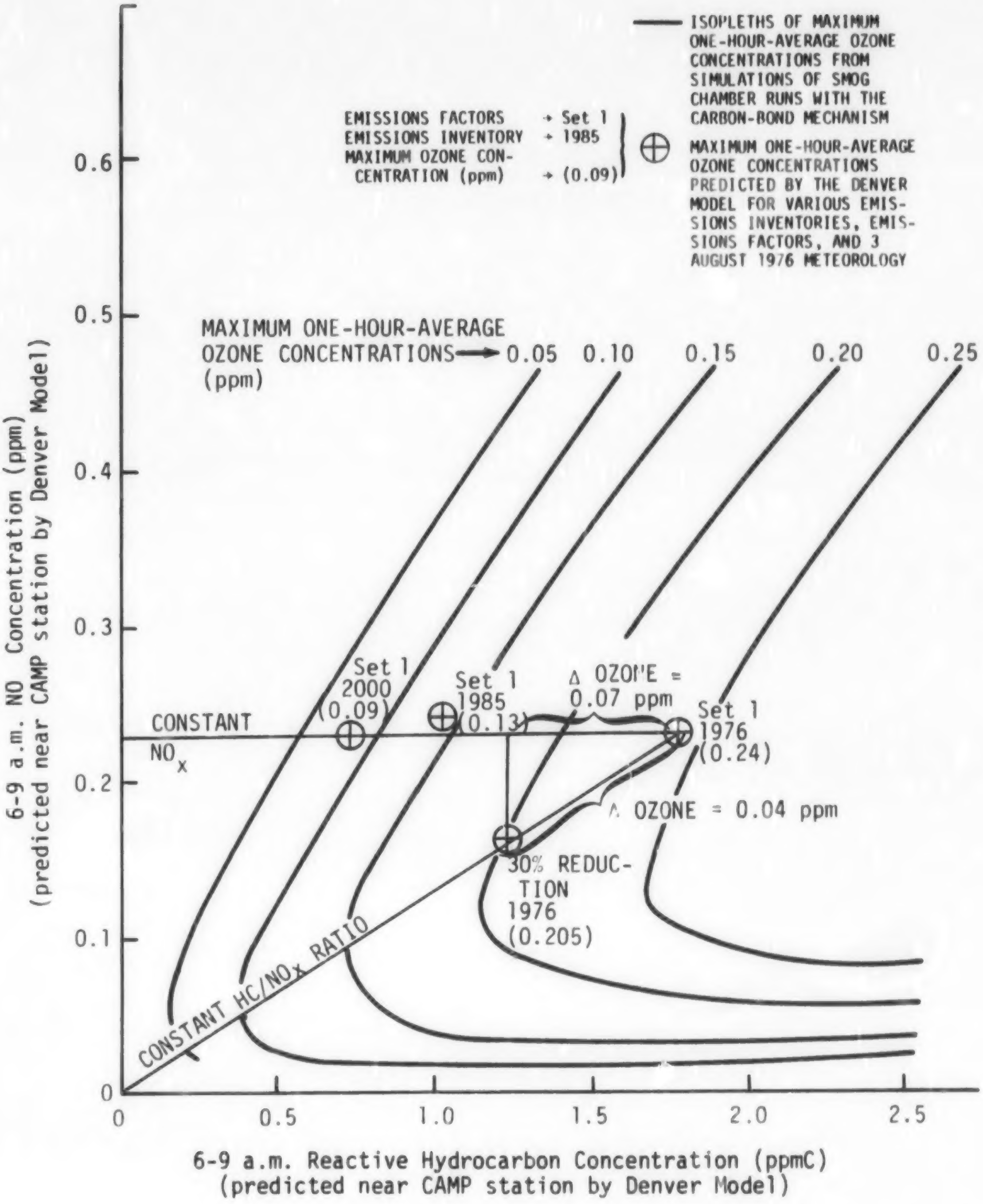


FIGURE V-2. OZONE ISOPLETH DIAGRAM

TABLE V-1. THE COST-EFFECTIVENESS OF VARIOUS METHODS FOR REDUCING HYDROCARBON EMISSIONS

Method	Dollars per Pound Reduction in HC Emissions	
Degreasing Controls	$ 0.0005	
Dry Cleaning Controls	0.014	Range for Stage II vapor recovery
Painting Substitutions	0.058	
Jet Engine Modification	0.058	
Jet Aircraft Towing	0.45	
Piston Aircraft Engine Mod.	1.81	
LDMV* Minor Exhaust Retrofit	1.75	
LDMV Catalytic Converter	2.19	
LDMV Evaporative Controls	2.31	
LDMV State Inspection/Maintenance	4.76	
LDMV Maintenance to Minimum Pollution Cap	10.65	
Modest Bus Improvement	9.25	
Modest Mileage Surcharge	9.25	
Heavy Mileage Surcharge	12.50	
Major Bus Improvements	21.45	

---

*LDMV = Light-Duty Motor Vehicles

Source: Venturini and Grandy (1975).

The conclusion is that hydrocarbon control approximates an optimally directed strategy for improving Denver's ozone air quality. The double hose vapor recovery system is a cost-effective technique for hydrocarbon control, but has limited potential since only a small fraction of the region's HC emissions can be controlled. The maximum effect on Denver's peak ozone concentrations should be about 1 pphm.

In the early stages of this project we uncovered two errors in the emissions inventories that had been used for some early runs of the Denver Model. Although these runs give no useful information on air quality in the future, the nature of the errors is such that they enable us to ascertain the effects on air quality of certain types of mitigation measures.

D. IMPLICATIONS FOR MITIGATION STRATEGIES OF ADDITIONAL SIMULATIONS

1. Effects of 30 Percent Reductions in All Emissions

The first error was the failure to include corrections to the emissions inventory to allow for Denver's atmospheric temperatures and pressure. This error resulted in an across-the-board reduction in all emissions of 30 percent. Simulation runs made with this inventory thus represent a scenario in which the imposition of emissions controls results in such an emissions reduction.

Figure V-3 shows the maximum one-hour-average ozone concentrations predicted over the entire region for two days in 1976 for both the corrected emissions inventory and the one with a 30 percent error. Note that for 28 July 1976 the reduction in the peak ozone concentration is 15 percent, from 20 pphm to 17 pphm. For 3 August 1976 the reduction is 12.5 percent, from 24 to 21 pphm. On both days the buildup of ozone with time is exactly the same for the two emissions inventories. Thus one may conclude that a 30 percent reduction in emissions results in a 15 percent reduction in the peak ozone concentration. This illustrates the nonlinearity of the ozone formation process, in that a given reduction in emissions results in only about one-half that reduction in the peak ozone concentration. Figure V-4 shows the total area in the region

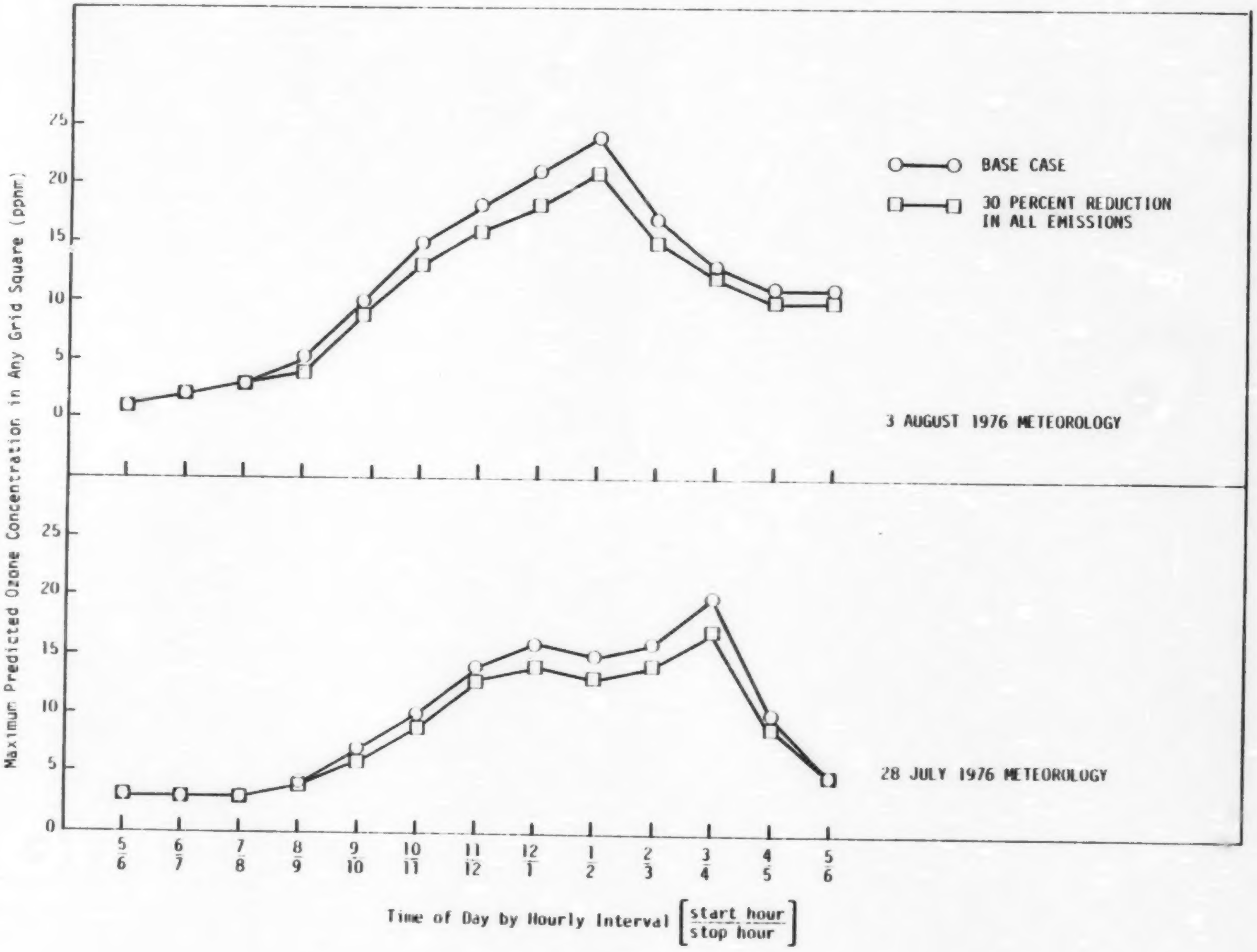
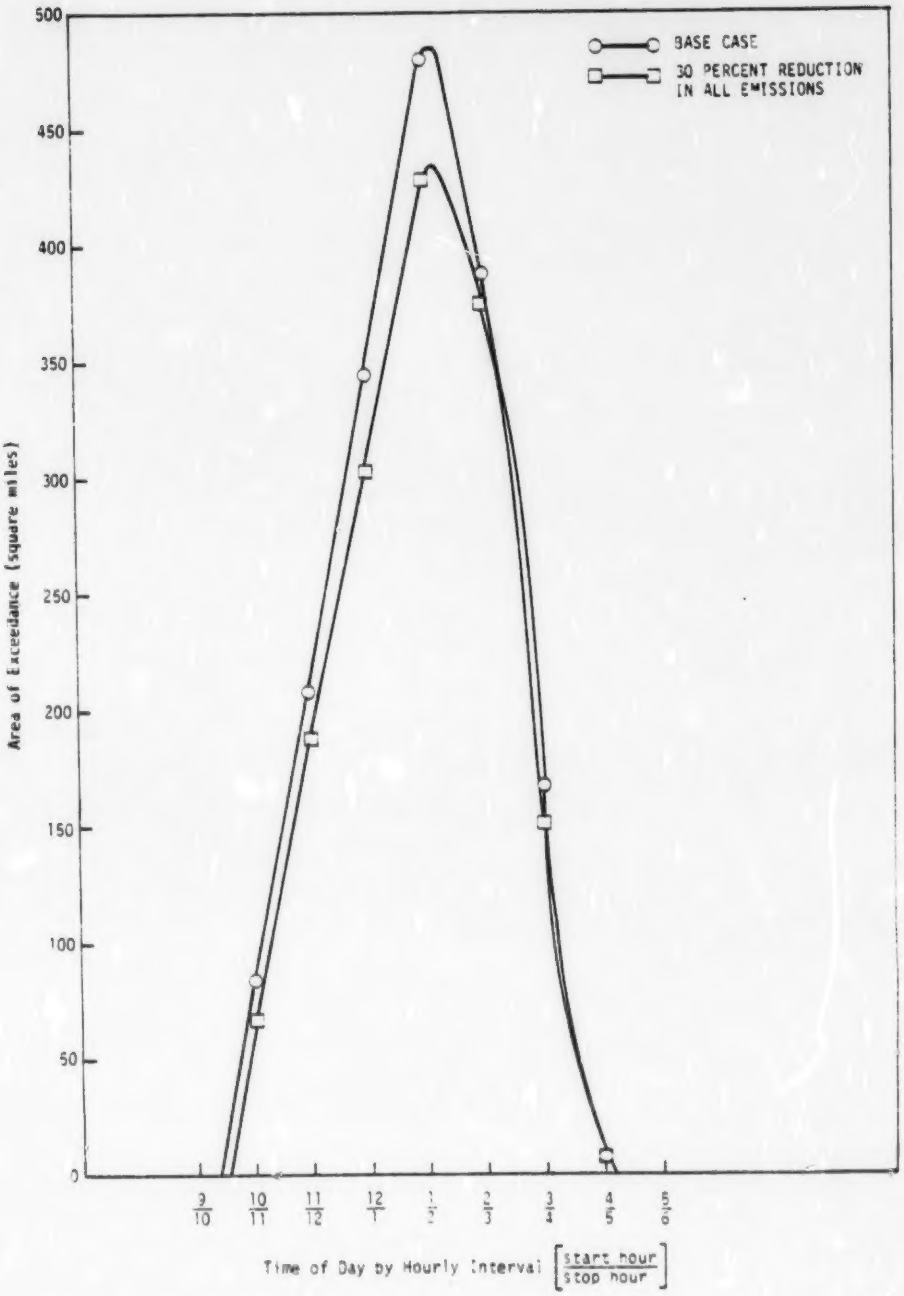
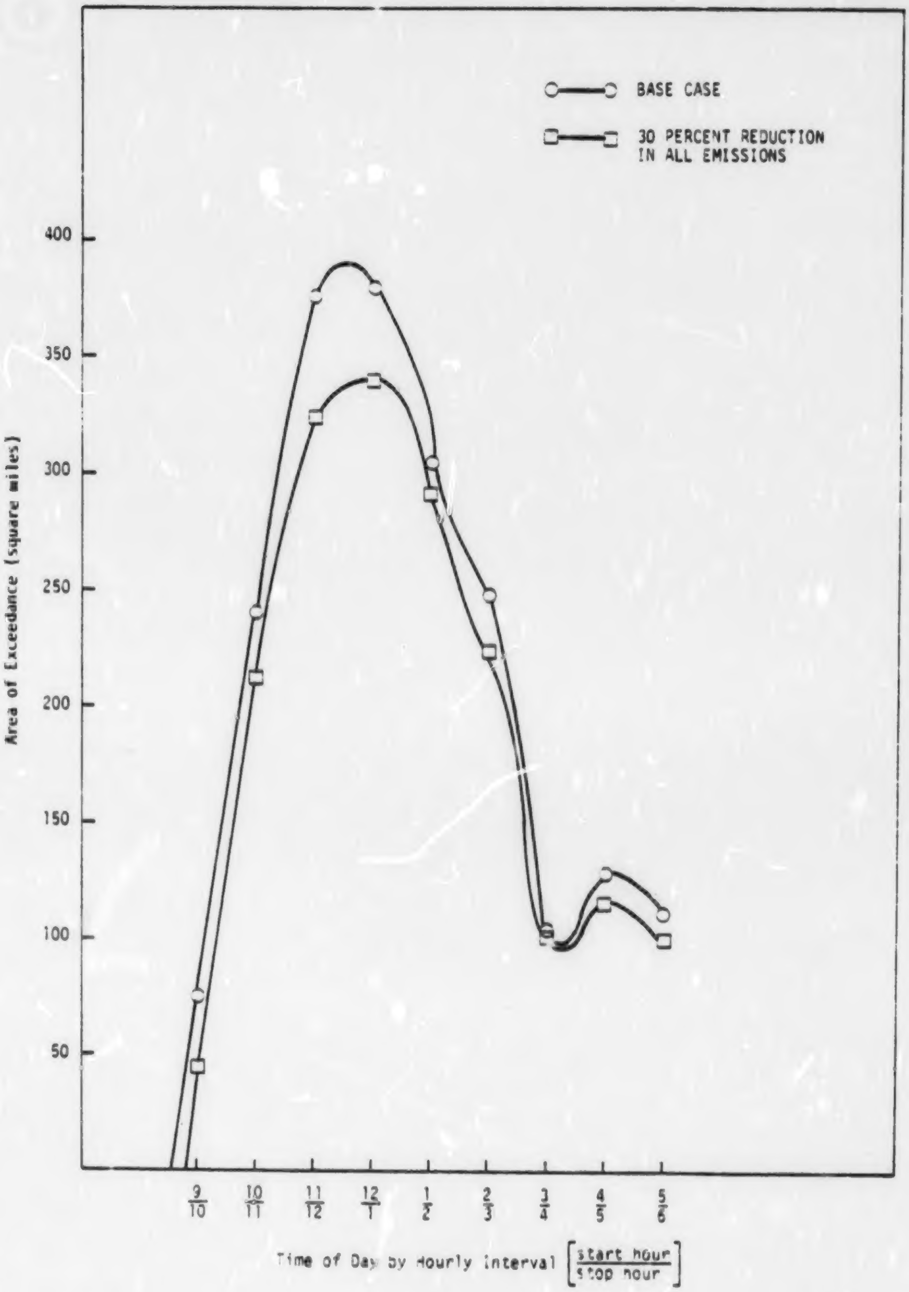


FIGURE V-3. THE EFFECT ON PREDICTED MAXIMUM OZONE CONCENTRATIONS OF A 30 PERCENT REDUCTION IN ALL EMISSIONS



(a) 28 July 1976 Meteorology

FIGURE V-4. AREA HAVING OZONE CONCENTRATIONS IN VIOLATION OF THE NAAQS



(b) 3 August 1976 Meteorology

FIGURE V-4. (Concluded)

for which the average ozone concentration exceeds the NAAQS for ozone (8 pphm) as a function of time of day. For this measure, the 30 percent reduction in emissions results in about a 10 percent reduction in area of exceedance.

2. Effects of Relaxation of the Federal NO_x Emissions Standard

The second error made in the emissions inventory was the use of an incorrect NO_x emissions factor for trucks in 1985. This resulted in the NO_x emissions from traffic being too high. For example, at 20 mph the emissions factor used corresponded to automobile NO_x emissions of 0.9 g/mile instead of 0.4 g/mile. We calculated that this error resulted in a spurious increase of 65 percent in the area-wide total NO_x emissions. The results of a model run made with this inventory may be used to obtain an estimate of the effect on ozone concentrations of a slowdown in the Federal timetable for reducing NO_x emissions from automobiles, while at the same time staying on schedule for hydrocarbon emissions reductions. Such a slowdown has been proposed because of problems with meeting the current Federally mandated guidelines.

Figure V-5 shows the effect of this increase in NO_x emissions on predicted peak ozone concentrations in the area in 1985. The figure shows that exceedances of the NAAQS for ozone would be eliminated by this change. The effect on peak concentrations for the 3 August 1976 meteorology is more pronounced than for the 28 July 1976 meteorology; the reductions are from 13 pphm to 5 pphm (a drop of 61 percent) and from 12 pphm to 8 pphm (a drop of 33 percent), respectively. A possible explanation for this difference is that the predicted peak ozone concentrations using the 28 July 1976 meteorology may be lower than they should be because of loss of material from the modeling region. Figure V-6 shows isopleths of predicted ozone concentrations using 28 July 1976 meteorology and an emissions inventory for 1985 that was not corrected for the error in NO_x emissions factors. It appears that between 10 a.m. and noon a considerable portion of the ozone cloud is outside the modeling region. Starting between noon and 1 p.m., the ozone cloud moves northward back into the modeling region. However, the Denver Model has

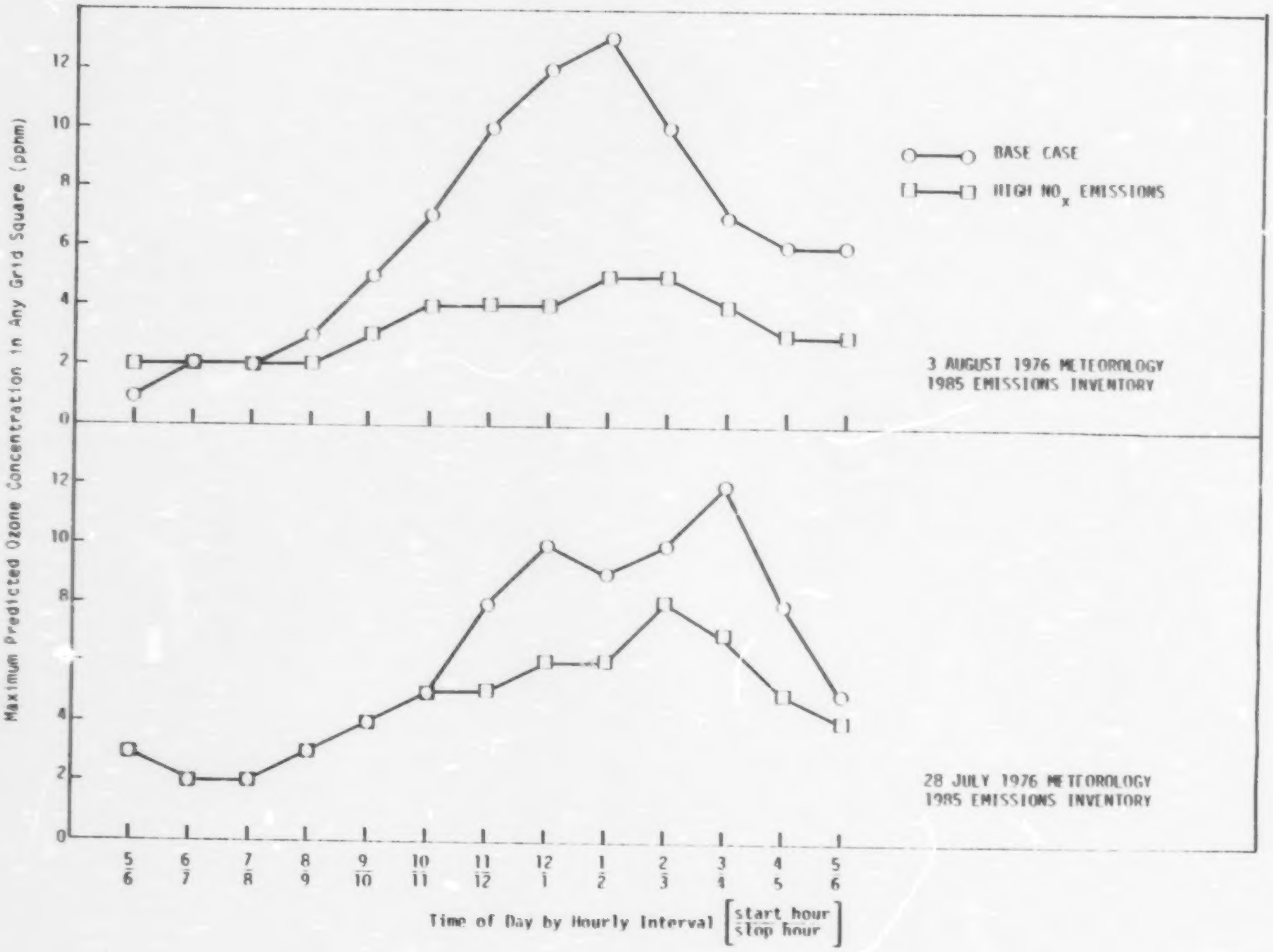
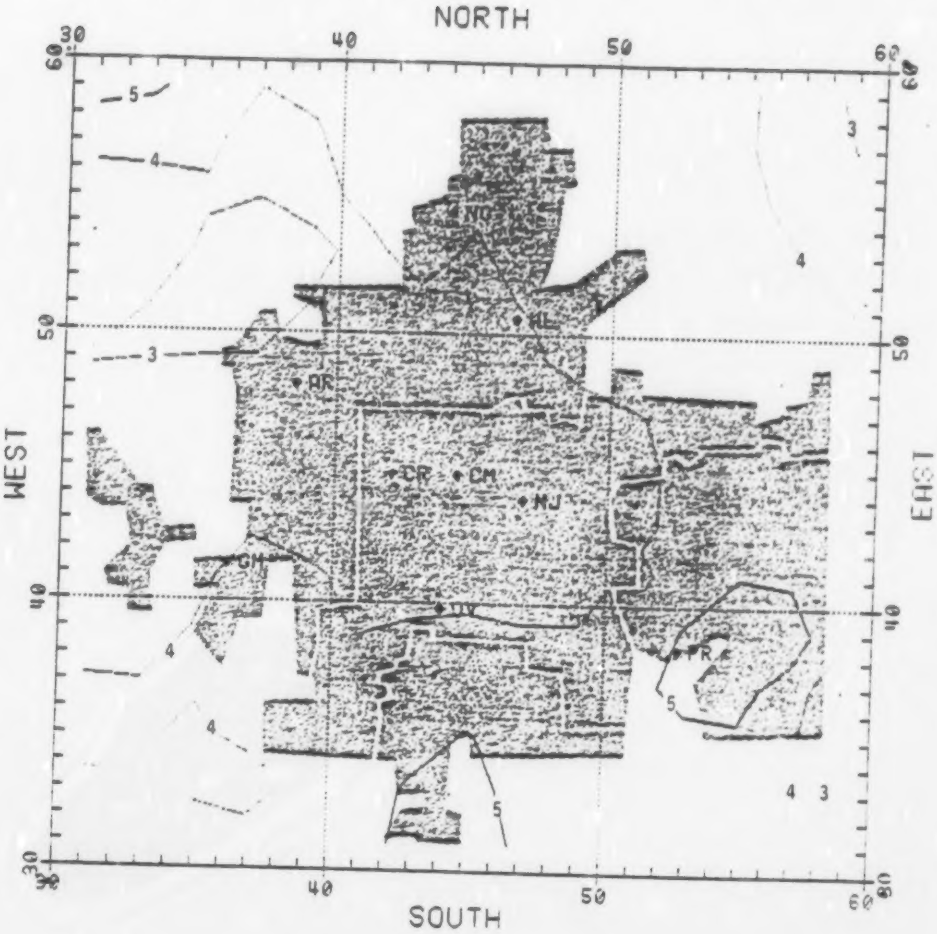
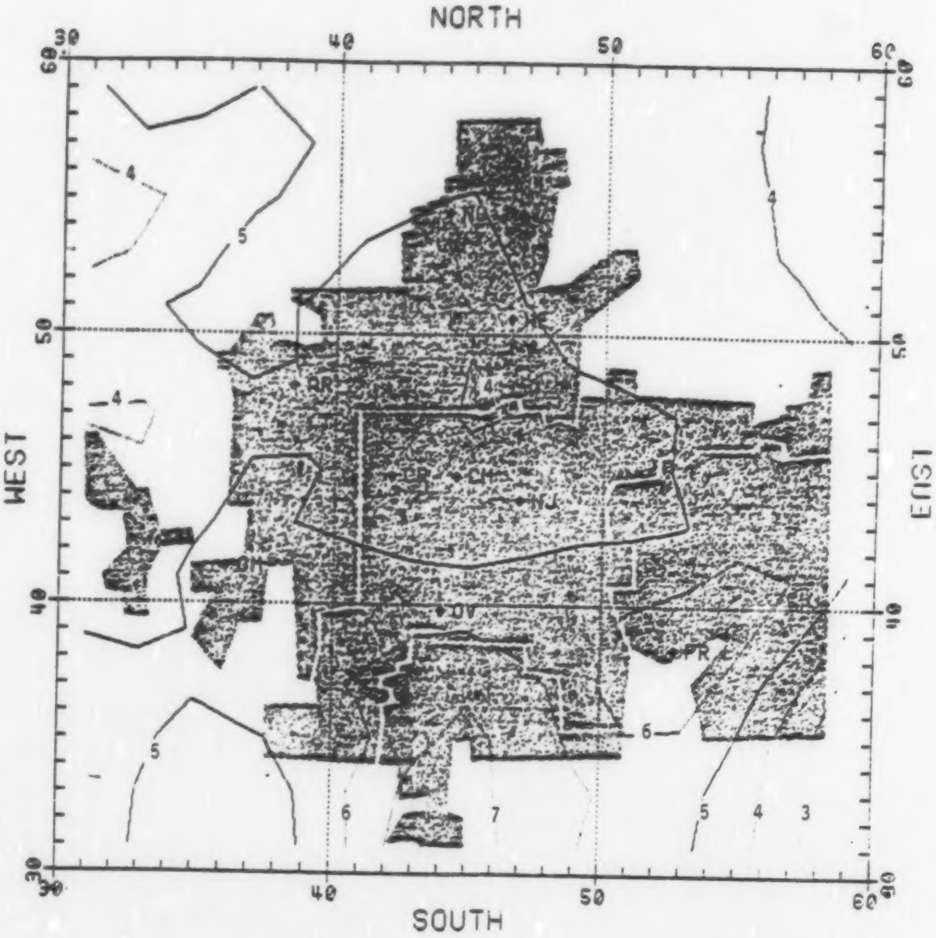


FIGURE V-5. THE EFFECT ON PREDICTED MAXIMUM OZONE CONCENTRATIONS OF AN INCREASE IN THE NO$_x$ EMISSION STANDARD


NORTH
SOUTH
WEST
EAST
30
40
50
60
5
4
3
HL
AR
CR
CM
NJ

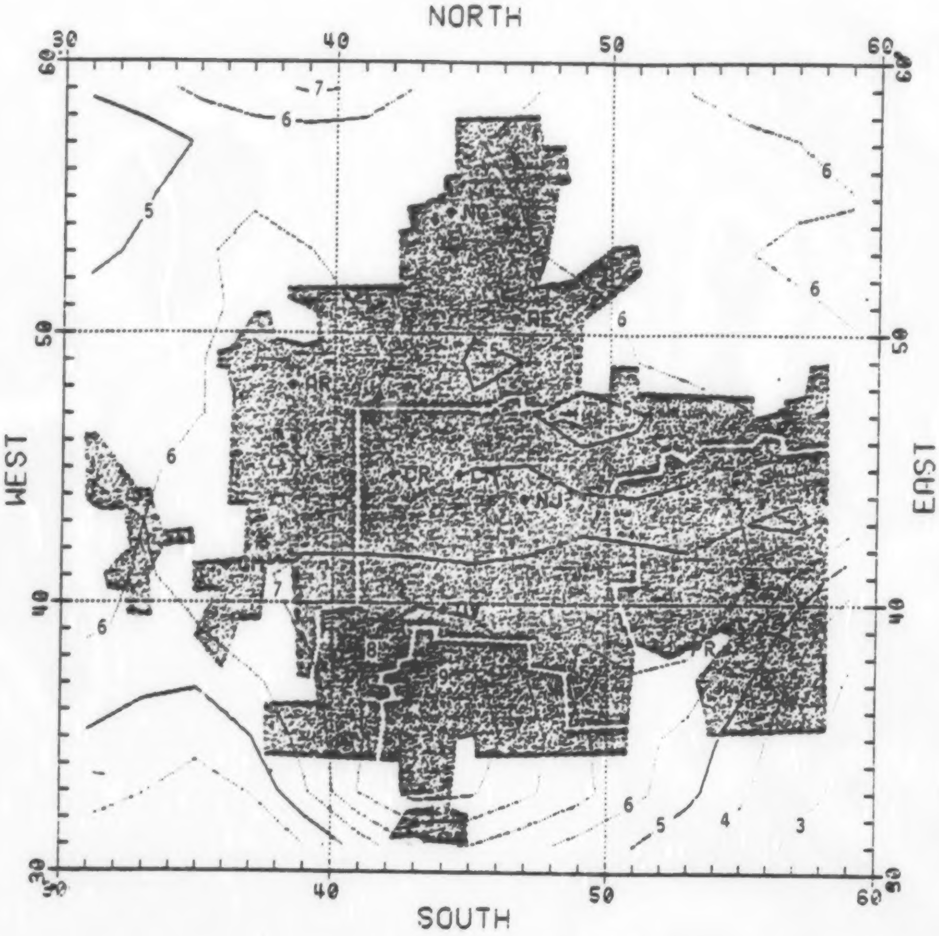
(a) 1000-1100 MST

FIGURE V-6. ISOPLETHS OF OZONE CONCENTRATIONS PREDICTED BY THE DENVER MODEL FOR 28 JULY 1976 METEOROLOGY AND 1985 EMISSIONS INVENTORY. Ozone isopleths in units of pphm.


NORTH
SOUTH
WEST
EAST
30
40
50
60
4
5
6
7
3
RR
CH
NJ
DV
PR

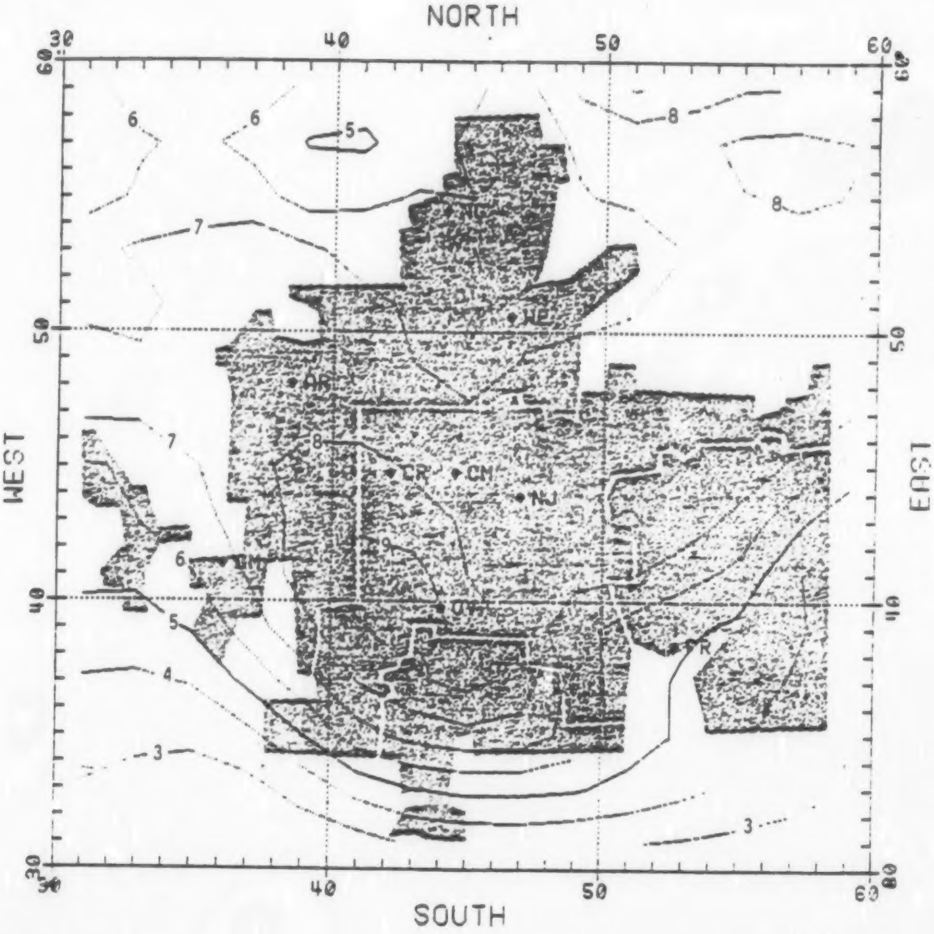
(b) 1100-1200 MST

FIGURE V-6. (Continued)


NORTH
SOUTH
WEST
EAST
30
40
50
60
7
6
5
4
3
8
NG
RE
AR
CR
NJ

(c) 1200-1300 MST

FIGURE V-6. (Continued)


NORTH
SOUTH
WEST
EAST
30
40
50
60
AR
CR
CM
NJ
WE
OV
GM
R
3
4
5
6
7
8
9

(d) 1200-1300 MST

FIGURE V-6. (Concluded)

no means to permit pollutants to reenter the modeling region. Thus the predicted ozone concentrations are artificially reduced. This effect is a possible explanation for the dip in the predicted peak ozone concentrations seen in Figure V-5 starting at noon.

Two conclusions may be drawn from the runs described here:

> A 30 percent reduction in all emissions resulted in only a 15 percent drop in the predicted peak ozone concentration.
> A relaxation of the NO_x emissions standard from 0.4 g/mile to 0.9 g/mile is predicted to result in up to a 60 percent reduction in the peak ozone concentration and to eliminate violations of the NAAQS for ozone for the Denver region for 1985 and 2000.

These two conclusions have important ramifications in terms of mitigation measures. The first shows that an across-the-board reduction of emissions by a given percentage may reduce the peak ozone concentration by only one-half that percentage. The second seems to promise great beneficial effects from a relaxation of NO_x emission standards. If the NO_x emissions standards are relaxed, however, the urban plume from Denver will contain more NO_x. Any downwind area releasing hydrocarbons into this plume will experience larger ozone concentrations because of reaction with the extra NO_2 from Denver. The predicted decrease in ozone concentrations within the Denver metropolitan region would, of course, be accompanied by increases in NO concentrations. Although there is no Federal air quality standard for NO, it is not clear that increased NO concentrations are desirable. NO oxidizes to NO_2, which is a regulated pollutant. Increased NO emissions do not necessarily lead to increased NO_2 concentrations in the Denver region for reasons similar to those explaining the ozone reduction. Increased downwind NO_2 concentrations could, however, be expected. Thus relaxation of the NO_x emission standard is not a panacea; if it is considered it must be with full account of all downwind effects.

VI EXPOSURE AND DOSAGE STUDIES

As indicated in Chapter III, simulations with the SAI Denver Model show that a substantial decrease in ambient ozone concentrations may be expected over the next 25 years. From the base case studies, peak ozone concentrations in the Denver metropolitan region are expected to drop from 24 pphm in 1976 to 13 pphm in 1985 and 9 pphm in 2000. The areal extent of violations of the NAAQS is projected to decrease from about 350 sq. mi. in 1976 to about 150 sq. mi. in 1985 and to less than 40 sq. mi. in 2000. To complete the analysis of the impact of improved air quality, we estimated the dosages and exposures that will be experienced by the human population within the Denver region. This chapter indicates briefly how ozone exposures and dosages were calculated, presents the results of the calculations, and discusses their significance.

It is important to note that the exposure and dosage calculations reported here depend on specific concentration distributions. The results therefore are only representative, and are not predictions in the sense that peak concentrations are. Other days with other wind patterns might produce equivalent peak ozone concentrations and even equivalent areas of exceedance, but if those peaks happened to occur at different locations, exposures and dosages might well be quite different.

A. DOSAGE CALCULATIONS

In the calculations performed here, the cumulative dosage of ozone is defined simply as the product of the population in a given area, the ozone concentration to which that population is exposed, and the length of time over which the exposure to that concentration occurs. The dosage provides a measure of the total amount of ozone present in the total volume of air that is inhaled by people over the time period of concern. This may be illustrated as follows. Let the dosage, D, be in units of pphm-person-hour. If the volume of air inhaled is V cubic meters per person-hour, the quantity of ozone (Q) present in the volume V may be estimated as

$$Q = DV\ (10^{-8}\ \text{cubic meters}) \quad .$$

If V is assumed to be a constant, then Q is proportional to D and the dosage D provides a measure of Q. It may be noted that the dosage provides no information as to the amount of ozone inhaled per person or the ambient ozone concentrations or time duration of the dosage. Mathematically, the dosage may be expressed as:

$$D(x,y) = \int_{t_1}^{t_2} P(x,y,t)C(x,y,t)dt$$

where D is the dosage of ozone from time t_1 to time t_2, P is the population, and C is the concentration of ozone.

The spatial variables x and y are used to indicate that D, P, and C vary with location. The population P is assumed to be a function of time (t) to account for the temporary redistribution of population that occurs during the daytime working hours.

B. EXPOSURE CALCULATIONS

The exposure to concentrations above a certain level η is defined here as the product of the number of people exposed and the time duration over which the concentration η is exceeded. Exposure calculations provide a measure of the number of people-hours in which the population is exposed to concentrations higher than a specified level. By using values of η equal to or greater than the NAAQS, it is possible to estimate the number of people exposed to excessively high ozone concentrations. Exposure calculations do not account for the impact of lower concentrations of ozone, and dosage calculations give us no indication of the concentration to which the individuals were exposed. Hence, exposure and dosage estimates complement each other: Exposures provide information on short periods of high concentrations and dosages indicate the impact of low or moderate pollutant concentrations of relatively longer duration.

Mathematically, exposure may be defined by

$$E(x,y,\eta) = \int_{t_1}^{t_2} P(x,y,t)\delta[C(x,y,t) - \eta]\,dt \quad ,$$

where $E(x,y,\eta)$ is the exposure corresponding to concentration η and the delta function δ equals 1 if the concentration at (x,y,t) is greater than or equal to η and 0 otherwise.

C. INPUTS NECESSARY FOR EXPOSURE AND DOSAGE CALCULATIONS

From the definitions of exposure and dosage, it is clear that ozone concentrations and population distributions must be estimated before ozone exposures and dosages can be calculated. In this section we discuss how ozone concentrations and population distributions were estimated and consider certain characteristics of these distributions.

1. Ozone Concentrations

The ozone concentrations used here were obtained from simulations with the SAI Denver Model for emissions in the years 1976, 1985, and 2000, using the meteorological conditions for 28 July 1976 and 3 August 1976. The predicted ozone concentrations are in the form of one-hour-averages over two mile square grid cells. (The results of these simulation runs are described in detail in Chapter III.) Since the conclusions of this study are only representative and since the results for the 28 July and 3 August meteorological conditions are qualitatively similar, results are presented here for 3 August only.

Figure VI-1 displays the cumulative ozone concentrations in pphm-hours for emissions in the years 1976, 1985, and 2000 and the 3 August 1976 meteorology. This figure shows integrated concentrations over a period of several hours, not hour-by-hour concentrations. It indicates the regions that experience high exposure to ozone during the day but not the exact location or time of occurrence of the peak one-hour-average ozone concentrations. Relatively high cumulative ozone concentrations are predicted to occur in the districts south of central Denver. The greatest cumulative concentrations are expected in the Sheridan-Englewood-Cherry Hills area for 1976 emissions, but shift to an area southeast of Columbine Valley for 1985 emissions and to an area south of Greenwood Village for 2000 emissions. Note that although the peak one-hour-average ozone concentrations predicted by the Denver Model for the base cases (Chapter III) drop sharply from 1976 to 1985 and again from 1985 to 2000, predicted reductions in the cumulative ozone concentrations are much more modest.

2. Population Distributions

Several methods have been used to estimate the population in the Denver metropolitan region; these are discussed in Appendix C. For the purposes of estimating dosage and exposure, populations as specified in the Sub-area Allocation Plan [SAP] (DRCOG, 1976) were used. The modeling region was first divided into 27 districts as indicated in Figure VI-2. Estimates of the population in each district in the years 1975, 1985, and 2000 were obtained from the SAP, and the population was assumed to be uniformly distributed within each district. These population data are summarized in Table VI-1. The population density in several suburbs will apparently approach that of central Denver in the year 2000, presumably due to the higher rate of growth in these areas. This is clearly brought out in Figure VI-3, which shows the increases in population from 1975 to 1985 and from 1985 to 2000. The southwestern suburbs of Lakewood and Jefferson County-Urban and the northern suburbs of Broomfield and Thornton are anticipated to be relatively high growth areas.

```
       1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30
 30   48  48  48  48  48  48  51  51  53  53  57  57  55  55  52  52  54  54  53  53  46  46  37  37  33  33  32  32  29  29
 29   48  48  48  48  48  48  51  51  53  53  57  57  55  55  52  52  54  54  58  53  46  46  37  37  33  33  32  32  29  29
 28   46  46  46  46  49  49  50  50  52  52  58  58  58  58  54  54  54  54  52  52  46  46  40  40  34  34  31  31  30  30
 27   46  46  46  46  49  49  50  50  52  52  58  58  58  58  54  54  54  54  52  52  46  46  40  40  34  34  31  31  30  30
                                     BROOMFIELD
 26   45  45  50  50  51  51  54  54  52  52  57  57  57  57  52  52  52  52  49  49  43  43  41  41  36  36  32  32  29  29
                                                             NORTHGLENN
 25   45  45  50  50  51  51  54  54  52  52  57  57  57  57  52  52  52  52  49  49  43  43  41  41  36  36  32  32  29  29
 24   48  48  54  54  56  56  58  58  57  57  56  56  55  55  51  51  50  50  45  45  43  43  38  38  36  36  36  36  29  29
                                             WESTMINSTER         THORNTON
 23   48  48  54  54  56  56  58  58  57  57  56  56  55  55  51  51  50  50  45  45  43  43  38  38  36  36  36  36  29  29
                                                         FDRL
 22   54  54  58  58  61  61  66  66  65  65  59  59  53  53  48  48  52  52  45  45  47  47  37  37  35  35  34  34  32  32
                                                         HGTS
 21   54  54  58  58  61  61  66  66  65  65  59  59  53  53  48  48  52  52  45  45  47  47  37  37  35  35  34  34  32  32
                                                                                     RCKY MNTN ARSNL
 20   53  53  58  58  65  65  69  69  70  70  67  67  57  57  50  50  53  53  50  50  44  44  38  38  37  37  34  34  32  32
                                     ARVADA                              COMMERCE
 19   53  53  58  58  65  65  69  69  70  70  67  67  57  57  50  50  53  53  50  50  44  44  38  38  37  37  34  34  32  32
 18   51  51  58  58  67  67  73  73  73  73  72  72  67  67  60  60  57  57  50  50  42  42  39  39  38  38  36  36  33  33
 17   51  51  58  58  67  67  73  73  73  73  72  72  67  67  60  60  57  57  50  50  42  42  39  39  38  38  36  36  33  33
                                 WHT. RDG                                        STAPL INTL
 16   53  53  61  61  71  71  78  78  81  81  84  84  75  75  73  73  69  69  57  57  45  45  41  41  40  40  37  37  35  35
         GOLDEN                              EDGEWATER
 15   53  53  61  61  71  71  78  78  81  81  84  84  75  75  73  73  69  69  57  57  45  45  41  41  40  40  37  37  35  35
                                                             D E N V E R                 AURORA
 14   54  54  63  63  71  71  81  81  86  86  89  89  82  82  83  83  76  76  71  71  60  60  50  50  44  44  39  39  36  36
 13   54  54  63  63  71  71  81  81  86  86  89  89  82  82  83  83  76  76  71  71  60  60  50  50  44  44  39  39  36  36
 12   51  51  62  62  73  73  85  85  95  95 101 101  98  98  94  94  87  87  82  82  73  73  59  59  52  52  43  43  39  39
                                                                     GLENDALE
 11   51  51  62  62  73  73  85  85  95  95 101 101  98  98  94  94  87  87  82  82  73  73  59  59  52  52  43  43  39  39
                                 LAKEWOOD
 10   49  49  58  58  72  72  88  88  97  97 105 105 109 109 109 109  96  96  87  87  79  79  65  65  52  52  48  48  42  42
  9   49  49  58  58  72  72  88  88  97  97 105 105 109 109 109 109  96  96  87  87  79  79  65  65  52  52  48  48  42  42
             MORRISON                            SHERIDAN    ENGLEWOOD
  8   46  46  55  55  68  68  85  85  95  95 105 105 114 114 115 115 106 106  88  88  78  78  64  64  58  58  53  53  42  42
                                                                 CHERRY HILLS
  7   46  46  55  55  68  68  85  85  95  95 105 105 114 114 115 115 106 106  88  88  78  78  64  64  58  58  53  53  42  42
  6   38  38  46  46  58  58  76  76  88  88  97  97 107 107 106 106 104 104  95  95  78  78  65  65  62  62  61  61  47  47
                                 JEFF CO                 LITTLETON       GREENWOOD VLG
  5   38  38  46  46  58  58  76  76  88  88  97  97 107 107 106 106 104 104  95  95  78  78  65  65  62  62  61  61  47  47
                                 URBAN       CLMBN VLY
  4   41  41  42  42  48  48  60  60  88  88  97  97 106 106  99  99 100 100  94  94  75  75  58  58  57  57  63  63  46  46
  3   41  41  42  42  48  48  60  60  88  88  97  97 106 106  99  99 100 100  94  94  75  75  58  58  57  57  63  63  46  46
                                                                                                  |   .
  2   38  38  43  43  49  49  58  58  70  70  77  77  87  87  77  77  81  81  78  78  62  62  51  51  52  52  49  49  40  40
  1   38  38  43  43  49  49  58  58  70  70  77  77  87  87  77  77  81  81  78  78  62  62  51  51  52  52  49  49  40  40
```

(a) Year 1976 Emissions

FIGURE VI-1. CUMULATIVE OZONE CONCENTRATIONS BETWEEN 500 AND 1300 HOURS PREDICTED BY THE DENVER MODEL. Concentrations are given in pphm-hours within one-square-mile grid cells for emissions in given year and 3 August 1976 meteorology; grid numbers listed on the left side and top of figure.

```
       1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30
30    44  44  43  43  41  41  42  42  43  43  46  46  44  44  44  44  49  49  49  49  44  44  36  36  32  32  32  32  29  29
29    44  44  43  43  41  41  42  42  43  43  46  46  44  44  44  44  49  49  49  49  44  44  36  36  32  32  32  32  29  29
28    43  43  41  41  42  42  41  41  42  42  46  46  47  47  45  45  49  49  40  40  43  43  38  38  33  33  30  30  29  29
27    43  43  41  41  42  42  41  41  42  42  46  46  47  47  45  45  49  49  40  40  43  43  38  38  33  33  30  30  29  29
                                      BROOMFIELD
26    42  42  44  44  43  43  43  43  40  40  44  44  43  43  40  40  45  45  45  45  40  40  39  39  35  35  32  32  29  29
                                                             NORTHGLENN
25    42  42  44  44  43  43  43  43  40  40  44  44  43  43  40  40  45  45  45  45  40  40  39  39  35  35  32  32  29  29
24    43  43  46  46  45  45  45  45  42  42  39  39  40  40  37  37  41  41  39  39  40  40  36  36  35  35  35  35  29  29
                                             WES.MINSTER        THORNTON
23    43  43  46  46  45  45  45  45  42  42  39  39  40  40  37  37  41  41  39  39  40  40  36  36  35  35  35  35  29  29
                                                       FDRL
22    45  45  46  46  46  46  47  47  43  43  38  38  35  35  33  33  39  39  37  37  42  42  34  34  33  33  33  33  32  32
                                                        HCTS
21    45  45  46  46  46  46  47  47  43  43  38  38  35  35  33  33  39  39  37  37  42  42  34  34  33  33  33  33  32  32
                                                                                     RCKY MNTN ARSNL
20    42  42  43  43  45  45  45  45  42  42  39  39  33  33  29  29  35  35  38  38  38  38  35  35  35  35  33  33  32  32
                                      ARVADA                            COMMERCE
19    42  42  43  43  45  45  45  45  42  42  39  39  33  33  29  29  35  35  38  38  38  38  35  35  35  35  33  33  32  32
18    38  38  40  40  44  44  42  42  40  40  38  38  36  36  32  32  33  33  31  31  33  33  33  33  35  35  35  35  33  33
17    38  38  40  40  44  44  42  42  40  40  38  38  36  36  32  32  33  33  31  31  33  33  33  33  35  35  35  35  33  33
                                WHT. RDC                                        STAPL INTL
16    39  39  41  41  44  44  45  45  44  44  43  43  37  37  36  36  38  38  34  34  35  35  35  35  37  37  36  36  34  34
          GOLDEN                        EDGEWATER
15    39  39  41  41  44  44  45  45  44  44  43  43  37  37  36  36  38  38  34  34  35  35  35  35  37  37  36  36  34  34
                                                             D E N V E R                  AURORA
14    41  41  42  42  43  43  46  46  44  44  43  43  38  38  41  41  41  41  44  44  44  44  39  39  39  39  37  37  35  35
13    41  41  42  42  43  43  46  46  44  44  43  43  38  38  41  41  41  41  44  44  44  44  39  39  39  39  37  37  35  35
12    41  41  42  42  46  46  50  50  51  51  51  51  48  48  46  46  47  47  51  51  51  51  45  45  44  44  40  40  38  38
                                                                      GLENDALE
11    41  41  42  42  46  46  50  50  51  51  51  51  48  48  46  46  47  47  51  51  51  51  45  45  44  44  40  40  38  38
                                  LAKEWOOD
10    42  42  45  45  48  48  53  53  53  53  55  55  56  56  57  57  54  54  55  55  55  55  49  49  44  44  43  43  41  41
 9    42  42  45  45  48  48  53  53  53  53  55  55  56  56  57  57  54  54  55  55  55  55  49  49  44  44  43  43  41  41
            MORRISON                            SHERIDAN  ENGLEWOOD
 8    43  43  46  46  49  49  54  54  55  55  59  59  62  62  66  66  64  64  56  56  55  55  51  51  49  49  47  47  39  39
                                                                CHERRY HILLS
 7    43  43  46  46  49  49  54  54  55  55  59  59  62  62  66  66  64  64  56  56  55  55  51  51  49  49  47  47  39  39
 6    37  37  41  41  45  45  51  51  54  54  57  57  61  61  65  65  66  66  60  60  54  54  50  50  52  52  53  53  42  42
                                 JEFF CO              LITTLETON     GREENWOOD VLG
 5    37  37  41  41  45  45  51  51  54  54  57  57  61  61  65  65  66  66  60  60  54  54  50  50  52  52  53  53  42  42
                                  URBAN        CLMBN VLY
 4    41  41  40  40  41  41  44  44  53  53  62  62  67  67  64  64  65  65  62  62  53  53  45  45  48  48  53  53  41  41
 3    41  41  40  40  41  41  44  44  53  53  62  62  67  67  64  64  65  65  62  62  53  53  45  45  48  48  53  53  41  41
 2    38  38  42  42  44  44  48  48  53  53  56  56  61  61  54  54  56  56  53  53  44  44  40  40  43  43  42  42  36  36
 1    38  38  42  42  44  44  48  48  53  53  56  56  61  61  54  54  56  56  53  53  44  44  40  40  43  43  42  42  36  36
```

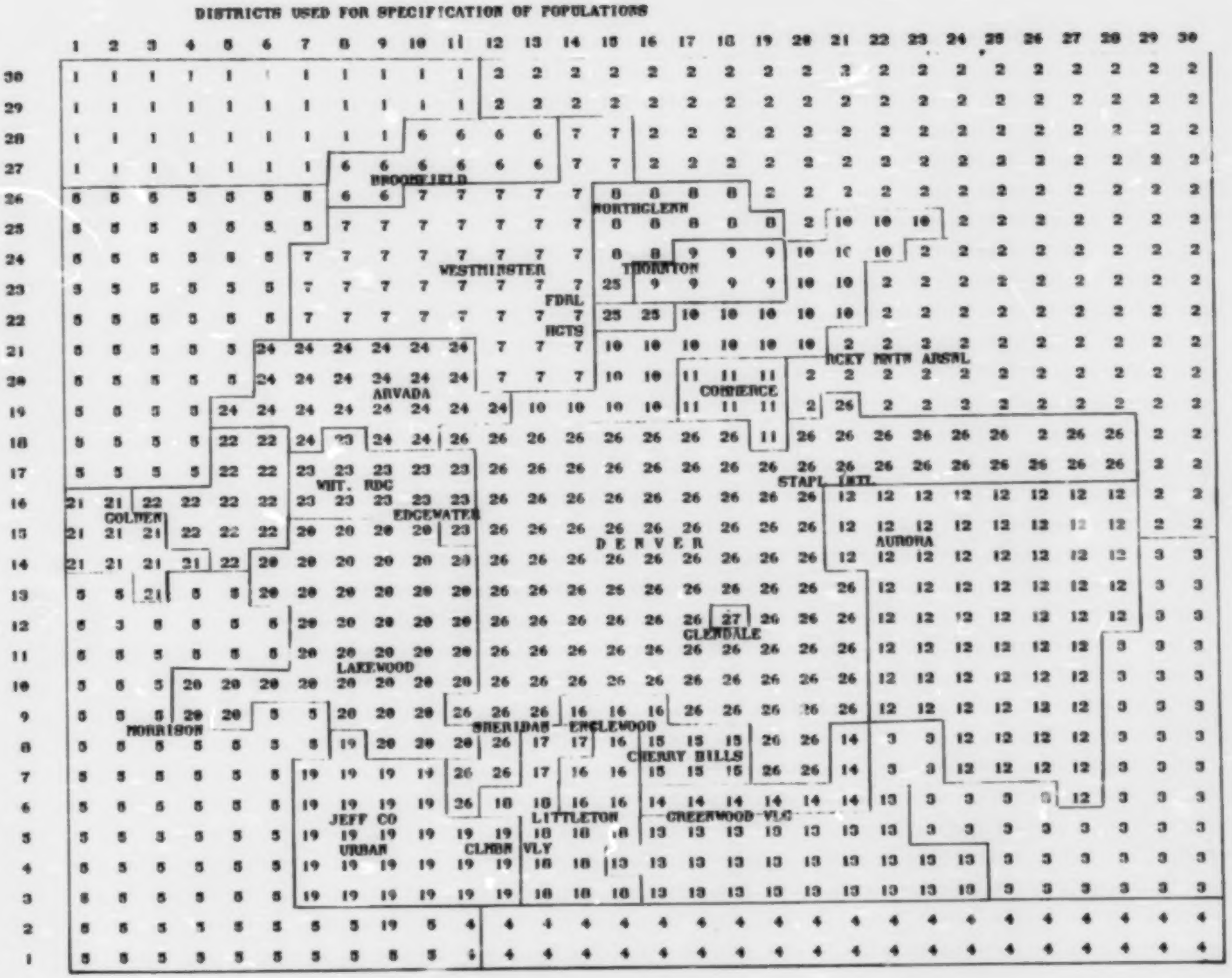
(b) Year 1985 Emissions

FIGURE VI-1 (Continued)

```
       1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30
30    44  44  42  42  41  41  43  43  44  44  47  47  46  46  45  45  49  49  48  48  43  43  36  36  33  33  33  33  29  29
29    44  44  42  42  41  41  43  43  44  44  47  47  46  46  45  45  49  49  48  48  43  43  36  36  33  33  33  33  29  29
28    42  42  40  40  41  41  39  39  40  40  44  44  44  44  42  42  47  47  47  47  42  42  38  38  33  33  31  31  30  30
27    42  42  40  40  41  41  39  39  40  40  44  44  44  44  42  42  47  47  47  47  42  42  38  38  33  33  31  31  30  30
                                     BROOMFIELD
26    40  40  42  42  40  40  39  39  37  37  39  39  39  39  37  37  42  42  43  43  39  39  38  38  35  35  32  32  29  29
                                                            NORTHGLENN
25    40  40  42  42  40  40  39  39  37  37  39  39  39  39  37  37  42  42  43  43  39  39  38  38  35  35  32  32  29  29
24    40  40  42  42  40  40  40  40  37  37  34  34  35  35  34  34  38  38  36  36  37  37  34  34  35  35  36  36  29  29
                                            WESTMINSTER        THORNTON
23    40  40  42  42  40  40  40  40  37  37  34  34  35  33  34  34  38  38  36  36  37  37  34  34  35  35  36  36  29  29
                                                       FDRL
22    41  41  41  41  40  40  40  40  37  37  32  32  30  30  29  29  36  36  34  34  39  39  32  32  32  32  34  34  32  32
                                                       HGTS
21    41  41  41  41  40  40  40  40  37  37  32  32  30  30  29  29  36  36  34  34  39  39  32  32  32  32  34  34  32  32
                                                                                    RCKY MNTN ARSNL
20    39  39  38  38  38  38  37  37  36  36  33  33  29  29  25  25  31  31  35  35  35  35  33  33  34  34  33  33  32  32
                                     ARVADA                            COMMERCE
19    39  39  38  38  38  38  37  37  36  36  33  33  29  29  25  25  31  31  35  35  35  35  33  33  34  34  33  33  32  32
18    34  34  34  34  35  35  33  33  32  32  32  32  30  30  27  27  29  29  27  27  31  31  31  31  34  34  34  34  33  33
17    34  34  34  34  35  35  33  33  32  32  32  32  30  30  27  27  29  29  27  27  31  31  31  31  34  34  34  34  33  33
                               WHT. RDG                                        STAPL INTL
16    35  35  34  34  35  35  34  34  35  35  34  34  29  29  29  29  31  31  28  28  31  31  32  32  35  35  35  35  34  34
         GOLDEN                        EDGEWATER
15    35  35  34  34  35  35  34  34  35  35  34  34  29  29  29  29  31  31  28  28  31  31  32  32  35  35  35  35  34  34
                                                            D E N V E R                  AURORA
14    37  37  35  35  34  34  33  33  34  34  33  33  28  28  31  31  31  31  33  33  38  38  36  36  36  36  36  36  35  35
13    37  37  35  35  34  34  33  33  34  34  33  33  28  28  31  31  31  31  33  33  38  38  36  36  36  36  36  36  35  35
12    38  38  37  37  37  37  36  36  39  39  38  38  35  35  33  33  35  35  39  39  42  42  39  39  41  41  39  39  37  37
                                                                     GLENDALE
11    38  38  37  37  37  37  36  36  39  39  38  38  35  35  33  33  35  35  39  39  42  42  39  39  41  41  39  39  37  37
                                 LAKEWOOD
10    39  39  39  39  40  40  40  40  41  41  40  40  38  38  39  39  39  39  42  42  45  45  43  43  40  40  41  41  39  39
 9    39  39  39  39  40  40  40  40  41  41  40  40  38  38  39  39  39  39  42  42  45  45  43  43  40  40  41  41  39  39
           MORRISON                               SHERIDAN   ENGLEWOOD
 8    41  41  41  41  40  40  42  42  43  43  43  43  41  41  47  47  47  47  43  43  46  46  45  45  45  45  44  44  36  36
                                                               CHERRY HILLS
 7    41  41  41  41  40  40  42  42  43  43  43  43  41  41  47  47  47  47  43  43  46  46  45  45  45  45  44  44  36  36
 6    36  36  38  38  39  39  41  41  42  42  42  42  42  42  48  48  51  51  47  47  45  45  44  44  46  46  47  47  38  38
                                JEFF CO              LITTLETON     GREENWOOD VLG
 5    36  36  38  38  39  39  41  41  42  42  42  42  42  42  48  48  51  51  47  47  45  45  44  44  46  46  47  47  38  38
                                 URBAN          CLMBN VLY
 4    39  39  38  38  36  36  36  36  42  42  47  47  47  47  49  49  52  52  50  50  44  44  40  40  42  42  48  48  38  38
 3    39  39  38  38  36  36  36  36  42  42  47  47  47  47  49  49  52  52  50  50  44  44  40  40  42  42  48  48  38  38
 2    38  38  40  40  41  41  42  42  42  42  43  43  47  47  44  44  46  46  46  46  39  39  36  36  39  39  38  38  33  33
 1    38  38  40  40  41  41  42  42  42  42  43  43  47  47  44  44  46  46  46  46  39  39  36  36  39  39  38  38  33  33
```

(c) Year 2000 Emissions

FIGURE VI-1 (Concluded)


BROOMFIELD
NORTHGLENN
WESTMINSTER
THORNTON
FDRL
HGTS
RCKY MNTN ARSNL
ARVADA
COMMERCE
WHT. RDG
STAPL INTL
GOLDEN
EDGEWATER
D E N V E R
AURORA
GLENDALE
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
JEFF CO
URBAN
LITTLETON
GREENWOOD VLG
CLMBN VLY

DISTRICTS USED FOR SPECIFICATION OF POPULATIONS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
30	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
29	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
28	1	1	1	1	1	1	1	1	1	6	6	6	6	7	7	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
27	1	1	1	1	1	1	1	6	6	6	6	6	6	7	7	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
26	5	5	5	5	5	5	5	6	6	7	7	7	7	7	8	8	8	8	2	2	2	2	2	2	2	2	2	2	2	2
25	5	5	5	5	5	5	5	7	7	7	7	7	7	7	8	8	8	8	8	2	10	10	10	2	2	2	2	2	2	2
24	5	5	5	5	5	5	7	7	7	7	7	7	7	7	8	8	9	9	9	10	10	10	2	2	2	2	2	2	2	2
23	5	5	5	5	5	5	7	7	7	7	7	7	7	7	25	9	9	9	9	10	10	2	2	2	2	2	2	2	2	2
22	5	5	5	5	5	5	7	7	7	7	7	7	7	7	25	25	10	10	10	10	10	2	2	2	2	2	2	2	2	2
21	5	5	5	5	5	24	24	24	24	24	24	7	7	7	10	10	10	10	10	10	2	2	2	2	2	2	2	2	2	2
20	5	5	5	5	5	24	24	24	24	24	24	7	7	7	10	10	11	11	11	2	2	2	2	2	2	2	2	2	2	2
19	5	5	5	5	24	24	24	24	24	24	24	24	10	10	10	10	11	11	11	2	26	2	2	2	2	2	2	2	2	2
18	5	5	5	5	22	22	24	23	24	24	26	26	26	26	26	26	26	26	11	26	26	26	26	26	26	2	26	26	2	2
17	5	5	5	5	22	22	23	23	23	23	23	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	2	2
16	21	21	22	22	22	22	23	23	23	23	23	26	26	26	26	26	26	26	26	26	12	12	12	12	12	12	12	12	2	2
15	21	21	21	22	22	22	20	20	20	20	23	26	26	26	26	26	26	26	26	26	12	12	12	12	12	12	12	12	2	2
14	21	21	21	21	22	20	20	20	20	20	20	26	26	26	26	26	26	26	26	26	12	12	12	12	12	12	12	12	3	3
13	5	5	21	5	5	20	20	20	20	20	20	26	26	26	26	26	26	26	26	26	26	12	12	12	12	12	12	12	3	3
12	5	5	5	5	5	5	20	20	20	20	20	26	26	26	26	26	26	27	26	26	26	12	12	12	12	12	12	12	3	3
11	5	5	5	5	5	5	20	20	20	20	20	26	26	26	26	26	26	26	26	26	26	12	12	12	12	12	12	3	3	3
10	5	5	5	20	20	20	20	20	20	20	20	26	26	26	26	26	26	26	26	26	26	12	12	12	12	12	12	3	3	3
9	5	5	5	20	20	5	5	20	20	20	26	26	26	16	16	16	26	26	26	26	26	12	12	12	12	12	12	3	3	3
8	5	5	5	5	5	5	5	19	20	20	20	26	17	17	16	15	15	15	26	26	14	3	3	12	12	12	12	3	3	3
7	5	5	5	5	5	5	19	19	19	19	26	26	17	16	16	15	15	15	26	26	14	3	3	12	12	12	12	3	3	3
6	5	5	5	5	5	5	19	19	19	19	26	18	18	16	16	14	14	14	14	14	14	13	3	3	3	3	12	3	3	3
5	5	5	5	5	5	5	19	19	19	19	19	19	18	18	18	13	13	13	13	13	13	13	3	3	3	3	3	3	3	3
4	5	5	5	5	5	5	19	19	19	19	19	19	18	18	13	13	13	13	13	13	13	13	13	13	3	3	3	3	3	3
3	5	5	5	5	5	5	19	19	19	19	19	19	18	18	18	13	13	13	13	13	13	13	13	13	3	3	3	3	3	3
2	5	5	5	5	5	5	5	5	19	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
1	5	5	5	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

FIGURE VI-2. POPULATION DISTRICTS SPECIFIED IN THE SUB-AREA ALLOCATION PLAN

TABLE VI-1. POPULATION BY DISTRICT

(Thousands of Persons)

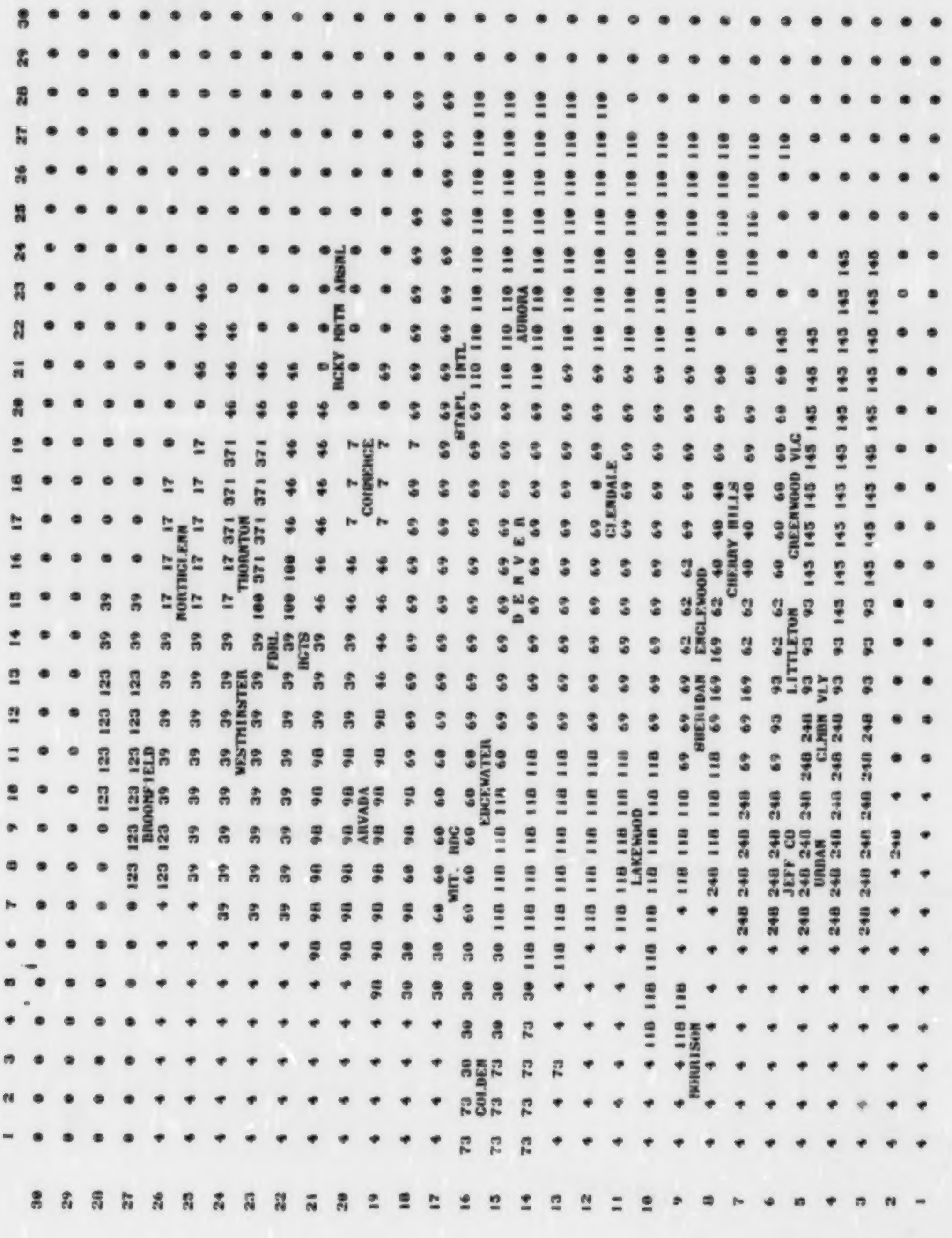
District No.	1975	1985	2000
1	0.00	0.00	0.00
2	10.50	14.20	14.80
3	.70	.90	1.20
4	0.00	0.00	0.00
5	.20	6.00	12.00
6	16.40	29.70	44.50
7	31.60	40.70	58.90
8	31.50	36.70	38.60
9	27.60	39.50	65.30
10	62.50	71.40	83.10
11	18.60	19.50	20.00
12	121.70	157.00	228.70
13	35.90	39.90	79.30
14	3.50	5.20	10.00
15	5.40	8.30	10.70
16	35.90	40.90	45.90
17	6.00	8.10	13.20
18	34.10	38.60	47.90
19	21.20	68.20	137.90
20	123.00	163.70	213.60
21	14.50	18.60	26.00
22	9.50	11.60	15.20
23	40.60	46.40	53.70
24	80.80	94.80	117.40
25	7.60	9.90	12.90
26	532.30	566.10	646.70
27	3.70	8.70	8.70

Source: DRCOG (1976).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
30	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
29	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
28	0	0	0	0	0	0	0	0	0	110	110	110	110	19	19	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
27	0	0	0	0	0	0	0	110	110	110	110	110	110	19	19	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
									BROOMFIELD																					
26	4	4	4	4	4	4	4	110	110	19	19	19	19	19	47	47	47	47	2	2	2	2	2	2	2	2	2	2	2	2
															NORTHGLENN															
25	4	4	4	4	4	4	4	19	19	19	19	19	19	19	47	47	47	47	47	2	35	35	35	2	2	2	2	2	2	2
24	4	4	4	4	4	4	19	19	19	19	19	19	19	19	47	47	170	170	170	35	35	35	2	2	2	2	2	2	2	2
											WESTMINSTER					THORNTON														
23	4	4	4	4	4	4	19	19	19	19	19	19	19	19	76	170	170	170	170	35	35	2	2	2	2	2	2	2	2	2
														FDRL																
22	4	4	4	4	4	4	19	19	19	19	19	19	19	19	76	76	35	35	35	35	35	2	2	2	2	2	2	2	2	2
														HGTS																
21	4	4	4	4	4	60	60	60	60	60	60	19	19	19	35	35	35	35	35	35	2	2	2	2	2	2	2	2	2	2
																					RCKY	MNTN	ARSNL							
20	4	4	4	4	4	60	60	60	60	60	60	19	19	19	35	35	12	12	12	2	2	2	2	2	2	2	2	2	2	2
									ARVADA								COMMERCE													
19	4	4	4	4	60	60	60	60	60	60	60	60	35	35	35	35	12	12	12	2	29	2	2	2	2	2	2	2	2	2
18	4	4	4	4	17	17	60	48	60	60	29	29	29	29	29	29	29	29	12	29	29	29	29	29	29	2	29	29	2	2
17	4	4	4	4	17	17	48	48	48	48	48	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	2	2
								WHT.	RDG																					
16	41	41	17	17	17	17	48	48	48	48	48	29	29	29	29	29	29	29	29	29	54	54	54	54	54	54	54	54	2	2
		GOLDEN								EDGEWATER										STAPL	INTL									
15	41	41	41	17	17	17	96	96	96	96	48	29	29	29	29	29	29	29	29	29	54	54	54	54	54	54	54	54	2	2
															DENVER								AURORA							
14	41	41	41	41	17	96	96	96	96	96	96	29	29	29	29	29	29	29	29	29	54	54	54	54	54	54	54	54	0	0
13	4	4	41	4	4	96	96	96	96	96	96	29	29	29	29	29	29	29	29	29	29	54	54	54	54	54	54	54	0	0
12	4	4	4	4	4	4	96	96	96	96	96	29	29	29	29	29	29	499	29	29	29	54	54	54	54	54	54	54	0	0
																	GLENDALE													
11	4	4	4	4	4	4	96	96	96	96	96	29	29	29	29	29	29	29	29	29	29	54	54	54	54	54	54	0	0	0
								LAKEWOOD																						
10	4	4	4	96	96	96	96	96	96	96	96	29	29	29	29	29	29	29	29	29	29	54	54	54	54	54	54	0	0	0
9	4	4	4	96	96	4	4	96	96	96	29	29	29	62	62	62	29	29	29	29	29	54	54	54	54	54	54	0	0	0
		MORRISON										SHERIDAN		ENGLEWOOD																
8	4	4	4	4	4	4	4	167	96	96	96	29	70	70	62	48	48	48	29	29	21	0	0	54	54	54	54	0	0	0
															CHERRY		HILLS													
7	4	4	4	4	4	4	167	167	167	167	29	29	70	62	62	48	48	48	29	29	21	0	0	54	54	54	54	0	0	0
6	4	4	4	4	4	4	167	167	167	167	29	45	45	62	62	21	21	21	21	21	21	14	0	0	0	0	54	0	0	0
								JEFF	CO				LITTLETON				GREENWOOD		VLG											
5	4	4	4	4	4	4	167	167	167	167	167	167	45	45	45	14	14	14	14	14	14	14	0	0	0	0	0	0	0	0
								URBAN			CLMBN		VLY																	
4	4	4	4	4	4	4	167	167	167	167	167	167	45	45	14	14	14	14	14	14	14	14	14	14	0	0	0	0	0	0
3	4	4	4	4	4	4	167	167	167	167	167	167	45	45	45	14	14	14	14	14	14	14	14	14	0	0	0	0	0	0
2	4	4	4	4	4	4	4	4	167	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	4	4	4	4	4	4	4	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(a) Increase from 1975 to 1985

FIGURE VI-3. INCREASE OF POPULATION (IN TENS OF PERSONS) IN ONE-SQUARE-MILE GRID CELLS IN THE DENVER METROPOLITAN AREA. Grid numbers are listed on the left side and top of figure.


BROOMFIELD
NORTHGLENN
WESTMINSTER
THORNTON
FDRL HGTS
ARVADA
COMMERCE
RCKY MNTN ARSNL
STAPL INTL
AURORA
D E N V E R
GLENDALE
WHT. RDG
GOLDEN
EDGEWATER
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
LITTLETON
GREENWOOD VLG
JEFF CO
URBAN
CLMBN VLY

(b) Increase from 1985 to 2000

FIGURE VI-3 (Concluded)

3. Adjustments to Population Distributions

The populations shown in Table VI-1 reflect the true population distributions only at times other than normal daytime working hours (0800 to 1500 MST). During normal working hours there is a substantial shift in the population because employment centers are generally not located near residential population centers. Since high ozone concentrations occur during the daylight hours, this temporary dislocation of population must be accounted for in estimating ozone dosages and exposures.

The adjustments required to estimate the population distribution during working hours may be carried out as follows. Let the employment in the i-th district be E_i and the residential population P_i. The total population within the entire modeling region is

$$P_T = \Sigma P_i \quad ,$$

and the total employment is

$$E_T = \Sigma E_i \quad .$$

Let α be a ratio defined by

$$\alpha = \frac{E_T}{P_T} = \frac{(\Sigma E_i)}{(\Sigma P_i)} \quad .$$

A number of people

$$(P_i)_{commute} = E_i - \alpha P_i$$

will commute into the i-th district during working hours to fill the jobs not filled by the local population. Hence the total population during working hours is given by

$$(P_i)_w = P_i + (E_i - \alpha P_i) \quad .$$

Note that the population adjustment may be positive, negative, or zero.

In order to estimate the adjusted populations during work hours, employment data are needed. Employment data are available by "super-districts" as indicated in Appendix C of this report. The 24-super-districts used for specification of employment are delineated in Figure VI-4. Employment in areas lying outside these super-districts is assumed to be negligible. Employment data are available for the years 1970 and 2000. The data for years 1975 and 1985 were obtained by linear interpolation. The employment by super-district is summarized in Table VI-2. Changes in employment between 1975 and 1985 and between 1985 and 2000 are shown in Figure VI-5. Large increases can be seen to occur in the districts to the south, the southeast, and the northeast of central Denver and also in the vicinity of Glendale.

Figure VI-6, showing the difference between the adjusted and residential population distributions, reveals the prevailing pattern whereby residents from outlying suburbs commute to central Denver during working hours.

D. EXPOSURE AND DOSAGE ESTIMATES

Dosages and exposures were estimated using the simulated ozone concentrations for 3 August 1976 meteorology and the population distributions in accordance with the Sub-area Allocation Plan (SAP). The population distributions were adjusted as noted above for temporary changes that occur during working hours.

Table VI-3 presents the estimated dosage and exposure over the Denver metropolitan region as a function of time of day. These results are also presented graphically in Figures VI-7 and VI-8. The dosage calculations show how the rate of increase of ozone dosage tends to be low in the early morning hours, increases to a maximum at mid-day and again gradually falls off at night. The cumulative dosage during the day appears to decrease by roughly 25 percent from 1976 to 1985 and then to increase by about 6.5 percent from 1985 to 2000. Dosages tend to reflect the average regionwide

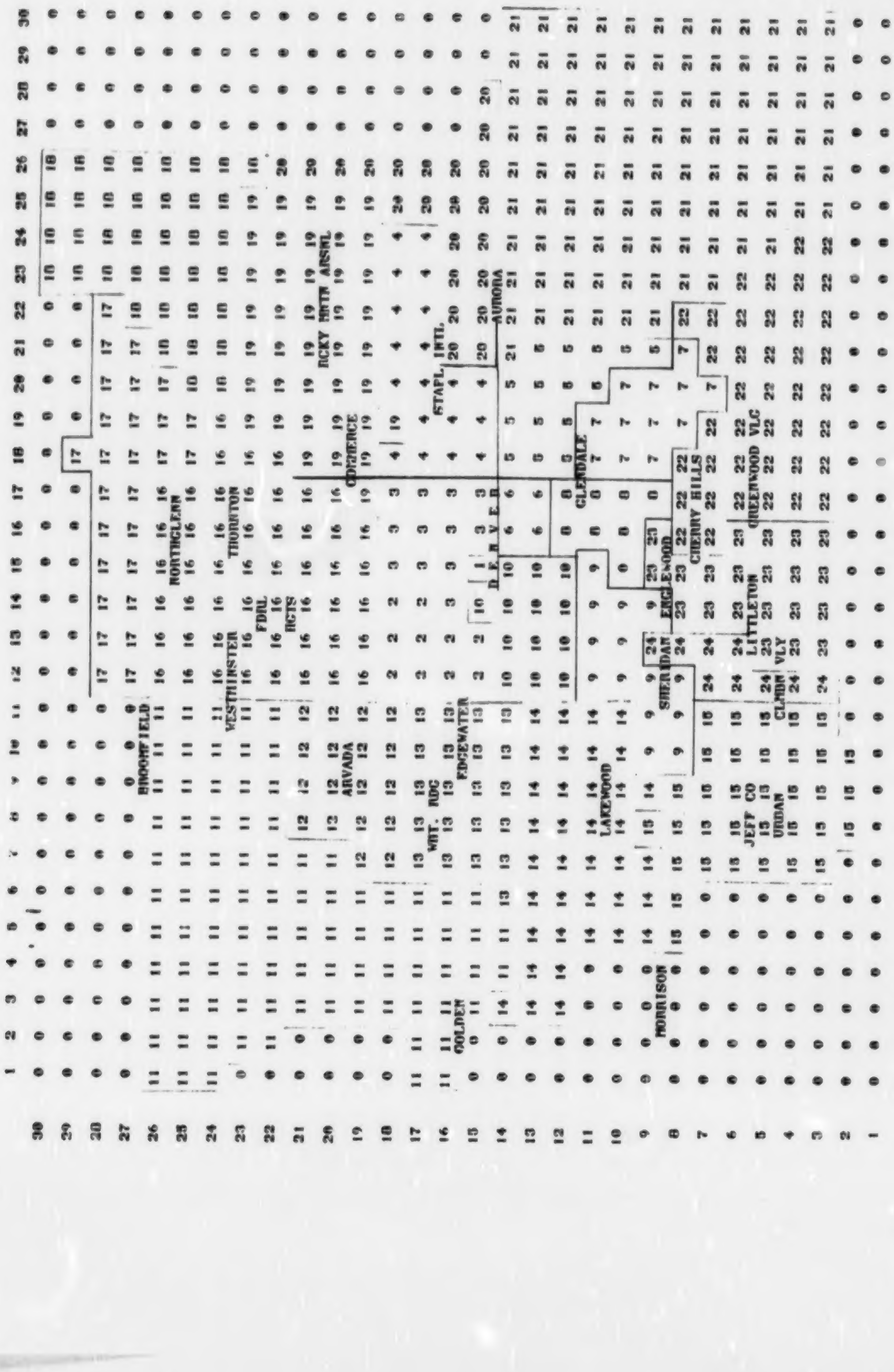

BROOMFIELD
NORTHGLENN
WESTMINSTER
THORNTON
FDRL HGTS
ARVADA
WHT. RDG
EDGEWATER
GOLDEN
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
LITTLETON
JEFF CO URBAN
CLMBN VLY
GREENWOOD VLG
GLENDALE
D E N V E R
COMMERCE
RCKY MNTN ARSNL
STAPL. INTL.
AURORA

FIGURE VI-4. SUPER-DISTRICTS USED FOR SPECIFICATION OF EMPLOYMENT

TABLE VI-2. EMPLOYMENT BY SUPER-DISTRICTS

(Thousands of Persons)

Super-District No.	Year 1975	1985	2000
0	0.00	0.00	0.00
1	48.10	48.40	48.90
2	21.60	31.20	45.60
3	62.70	70.20	81.40
4	28.90	36.60	48.00
5	36.00	42.80	53.00
6	32.00	35.50	40.60
7	21.70	37.00	60.00
8	24.40	34.10	46.50
9	13.40	22.70	36.60
10	54.00	56.10	59.20
11	20.80	28.30	39.60
12	10.80	15.50	22.40
13	26.30	34.50	40.00
14	20.60	28.70	40.90
15	10.50	16.60	25.70
16	37.40	48.60	65.40
17	2.00	4.70	8.70
18	3.70	4.80	6.50
19	12.30	16.10	21.70
20	14.80	28.20	44.50
21	17.50	28.60	45.20
22	16.30	37.60	69.40
23	31.10	39.60	52.40
24	9.60	19.40	34.00

Source: DRCOG (1973).

```
       1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30
  30   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   2   2   2   2   0   0   0   0
  29   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   9   0   0   0   0   2   2   2   2   0   0   0   0
  28   0   0   0   0   0   0   0   0   0   0   0   9   9   9   9   9   9   9   9   9   9   9   2   2   2   2   0   0   0   0
  27   0   0   0   0   0   0   0   0   0   0   0   9   9   9   9   9   9   9   9   9   9   2   2   2   2   2   0   0   0   0
                                     BROOMFIELD
  26   8   8   8   8   8   8   8   8   8   8   8  21  21  21  21  21  21   9   9   9   2   2   2   2   2   2   0   0   0   0
                                                             NORTHGLENN
  25   8   8   8   8   8   8   8   8   8   8   8  21  21  21  21  21  21   9   9   2   2   2   2   2   2   2   0   0   0   0
  24   8   8   8   8   8   8   8   8   8   8   8  21  21  21  21  21  21  21  21   2   2   2   2   2   2   2   0   0   0   0
                                             WESTMINSTER         THORNTON
  23   0   8   8   8   8   8   8   8   8   8   8  21  21  21  21  21  21  21   9   9   9   9   9   9   9   2   0   0   0   0
                                                         FDRL
  22   0   8   8   8   8   8   8   8   8   8   8  21  21  21  21  21  21  21   9   9   9   9   9   9   9  60   0   0   0   0
                                                         HGTS
  21   0   0   8   8   8   8   8  26  26  26  26  21  21  21  21  21  21   9   9   9   9   9   9   9   9  60   0   0   0   0
                                                                                     RCKY MNTN ARSNL
  20   0   0   8   8   8   8   8  26  26  26  26  21  21  21  21  21  21   9   9   9   9   9   9   9   9  60   0   0   0   0
                                     ARVADA                         COMMERCE
  19   0   0   8   8   8   8  26  26  26  26  26  21  21  21  21  21   9   9   9   9   9   9   9   9   9  60   0   0   0   0
  18   0   0   8   8   8   8  26  26  26  26  26  96  96  96  62  62  62  40   9  40  40  40  40  40  60  60   0   0   0   0
  17   8   8   8   8   8   8  39  39  39  39  39  96  96  96  62  62  62  40  40  40  40  40  40  40  60  60   0   0   0   0
                                 WHT. RDG                                       STAPL INTL
  16   8   8   8   8   8   8  39  39  39  39  39  96  96  62  62  62  62  40  40  40  60  60  60  60  60  60   0   0   0   0
         GOLDEN                          EDGEWATER
  15   0   0   8   8   8   8  39  39  39  39  39  96  96  16  30  62  62  40  40  40  60  60  60  60  60  60  60  60   0   0
                                                             D E N V E R                 AURORA
  14   0   0  21   8   8  39  39  39  39  39  39  16  16  16  16  87  87  45  45  45  11  11  11  11  11  11  11  11  11  11
  13   0   0  21  21  21  21  21  21  21  21  21  16  16  16  16  87  87  45  45  45  45  11  11  11  11  11  11  11  11  11
  12   0   0  21  21  21  21  21  21  21  21  21  16  16  16  16 138 138  45  45  45  45  11  11  11  11  11  11  11  11  11
                                                                     GLENDALE
  11   0   0   0   0  21  21  21  21  21  21  21  66  66  66  66 138 138 127 127  45  45  11  11  11  11  11  11  11  11  11
                                 LAKEWOOD
  10   0   0   0   0  21  21  21  21  21  21  21  66  66  66   0 138 138 127 127 127  45  11  11  11  11  11  11  11  11  11
   9   0   0   0   0  21  21  21  17  21  66  66  66 108  66  40  40 138 127 127 127  45  11  11  11  11  11  11  11  11  11
             MORRISON                            SHERIDAN  ENGLEWOOD
   8   0   0   0   0  17  17  17  17  17  66  66  66 108  40  40  53  53  53 127 127 127  53  11  11  11  11  11  11  11  11
                                                                 CHERRY HILLS
   7   0   0   0   0   0   0  17  17  17  17  17 108 108  40  40  53  53  53  53 127  53  53  11  11  11  11  11  11  11  11
   6   0   0   0   0   0   0  17  17  17  17  17 108 108  40  40  40  53  53  53  53  53  53  53  11  11  11  11  11  11  11
                                 JEFF CO             LITTLETON       GREENWOOD VLG
   5   0   0   0   0   0   0  17  17  17  17  17 108  40  40  40  40  53  53  53  53  53  53  53  11  11  11  11  11  11  11
                                 URBAN           CLMBN VLY
   4   0   0   0   0   0   0  17  17  17  17  17 108  40  40  40  40  53  53  53  53  53  53  53  53  11  11  11  11  11  11
   3   0   0   0   0   0   0  17  17  17  17  17 108  40  40  40  40  53  53  53  53  53  53  53  53  11  11  11  11  11  11
   2   0   0   0   0   0   0   0  17  17  17   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   1   0   0   0   0   0   0   0   0   6   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
```

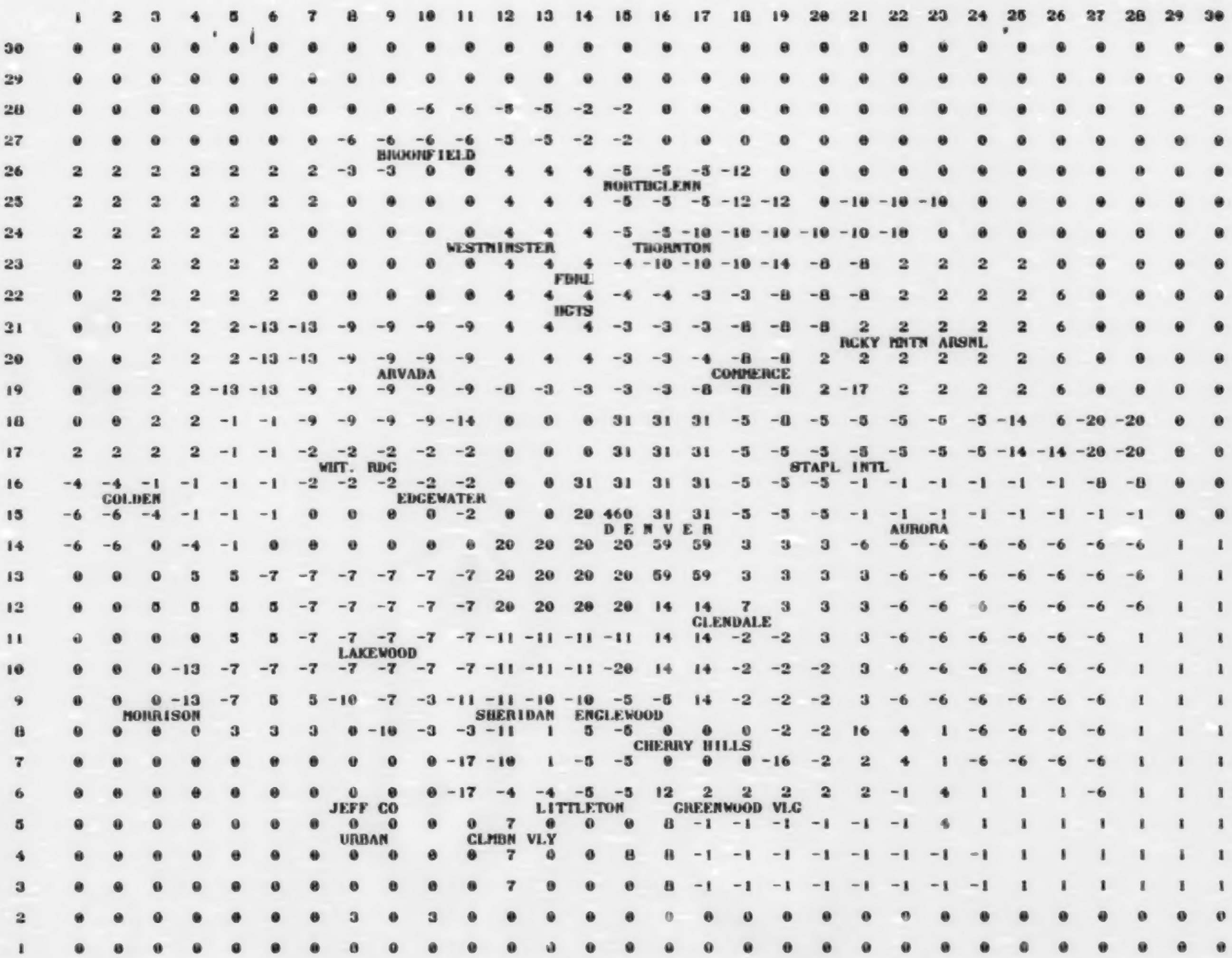
(a) Between 1975 and 1985

FIGURE VI-5. INCREASE OF EMPLOYMENT (IN TENS OF PERSONS) IN ONE-SQUARE-MILE GRID CELLS IN THE DENVER METROPOLITAN REGION. Grid numbers are listed on the left side and top of figure.

```
       1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30
  30   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   4   4   4   4   0   0   0   0
  29   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0  14   0   0   0   0   4   4   4   4   0   0   0   0
  28   0   0   0   0   0   0   0   0   0   0   0  14  14  14  14  14  14  14  14  14  14  14   4   4   4   4   0   0   0   0
  27   0   0   0   0   0   0   0   0   0   0   0  14  14  14  14  14  14  14  14  14  14   4   4   4   4   4   0   0   0   0
                                     BROOMFIELD
  26  12  12  12  12  12  12  12  12  12  12  12  32  32  32  32  32  32  14  14  14   4   4   4   4   4   4   0   0   0   0
                                                            NORTHGLENN
  25  12  12  12  12  12  12  12  12  12  12  12  32  32  32  32  32  32  14  14   4   4   4   4   4   4   4   0   0   0   0
  24  12  12  12  12  12  12  12  12  12  12  12  32  32  32  32  32  32  32  32   4   4   4   4   4   4   4   0   0   0   0
                                            WESTMINSTER        THORNTON
  23   0  12  12  12  12  12  12  12  12  12  12  32  32  32  32  32  32  32  14  14  14  14  14  14  14   4   0   0   0   0
                                                       FDRL
  22   0  12  12  12  12  12  12  12  12  12  12  32  32  32  32  32  32  32  14  14  14  14  14  14  14  74   0   0   0   0
                                                       HGTS
  21   0   0  12  12  12  12  12  38  38  38  38  32  32  32  32  32  32  14  14  14  14  14  14  14  14  74   0   0   0   0
                                                                                    RCKY MNTN ARSNL
  20   0   0  12  12  12  12  12  38  38  38  38  32  32  32  32  32  32  14  14  14  14  14  14  14  14  74   0   0   0   0
                                     ARVADA                            COMMERCE
  19   0   0  12  12  12  12  38  38  38  38  38  32  32  32  32  32  14  14  14  14  14  14  14  14  14  74   0   0   0   0
  18   0   0  12  12  12  12  38  38  38  38  38 143 143 143  93  93  93  59  14  59  59  59  59  59  74  74   0   0   0   0
  17  12  12  12  12  12  12  26  26  26  26  26 143 143 143  93  93  93  59  59  59  59  59  59  59  74  74   0   0   0   0
                               WHT. RDG                                        STAPL INTL.
  16  12  12  12  12  12  12  26  26  26  26  26 143 143  93  93  93  93  59  59  59  74  74  74  74  74  74   0   0   0   0
         GOLDEN                        EDGEWATER
  15   0   0  12  12  12  12  26  26  26  26  26 143 143  23  50  93  93  59  59  59  74  74  74  74  74  74  74  74   0   0
                                                            D E N V E R                  AURORA
  14   0   0  32  12  12  26  26  26  26  26  26  23  23  23  23 127 127  68  68  68  17  17  17  17  17  17  17  17  17  17
  13   0   0  32  32  32  32  32  32  32  32  32  23  23  23  23 127 127  68  68  68  68  17  17  17  17  17  17  17  17  17
  12   0   0  32  32  32  32  32  32  32  32  32  23  23  23  23 205 205  68  68  68  68  17  17  17  17  17  17  17  17  17
                                                                     GLENDALE
  11   0   0   0   0  32  32  32  32  32  32  32  99  99  99  99 205 205 191 191  68  68  17  17  17  17  17  17  17  17  17
                                 LAKEWOOD
  10   0   0   0   0  32  32  32  32  32  32  32  99  99  99   0 205 205 191 191 191  68  17  17  17  17  17  17  17  17  17
   9   0   0   0   0  32  32  32  26  32  99  99  99 162  99  60  60 205 191 191 191  68  17  17  17  17  17  17  17  17  17
           MORRISON                            SHERIDAN  ENGLEWOOD
   8   0   0   0   0  26  26  26  26  26  99  99  99 162  60  60  79  79  79 191 191 191  79  17  17  17  17  17  17  17  17
                                                               CHERRY HILLS
   7   0   0   0   0   0   0  26  26  26  26  26 162 162  60  60  79  79  79  79 191  79  79  17  17  17  17  17  17  17  17
   6   0   0   0   0   0   0  26  26  26  26  26 162 162  60  60  60  79  79  79  79  79  79  79  17  17  17  17  17  17  17
                                JEFF CO              LITTLETON     GREENWOOD VLG
   5   0   0   0   0   0   0  26  26  26  26  26 162  60  60  60  60  79  79  79  79  79  79  79  17  17  17  17  17  17  17
                                 URBAN        CLMBN VLY
   4   0   0   0   0   0   0  26  26  26  26  26 162  60  60  60  60  79  79  79  79  79  79  79  79  17  17  17  17  17  17
   3   0   0   0   0   0   0  26  26  26  26  26 162  60  60  60  60  79  79  79  79  79  79  79  79  17  17  17  17  17  17
   2   0   0   0   0   0   0   0  26  26  26   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
```

(b) Between 1985 and 2000

FIGURE VI-5 (Concluded)


BROOMFIELD
NORTHGLENN
WESTMINSTER
THORNTON
FDRL
HGTS
RCKY MNTN ARSNL
ARVADA
COMMERCE
WHT. RDG
STAPL INTL
GOLDEN
EDGEWATER
D E N V E R
AURORA
GLENDALE
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
JEFF CO
LITTLETON
GREENWOOD VLG
URBAN
CLMBN VLY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	-6	-6	-5	-5	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	-6	-6	-6	-6	-5	-5	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	2	2	2	2	2	2	2	-3	-3	0	0	4	4	4	-5	-5	-5	-12	0	0	0	0	0	0	0	0	0	0	0	0
25	2	2	2	2	2	2	2	0	0	0	0	4	4	4	-5	-5	-5	-12	-12	0	-10	-10	-10	0	0	0	0	0	0	0
24	2	2	2	2	2	2	0	0	0	0	0	4	4	4	-5	-5	-10	-10	-10	-10	-10	-10	0	0	0	0	0	0	0	0
23	0	2	2	2	2	2	0	0	0	0	0	4	4	4	-4	-10	-10	-10	-14	-8	-8	2	2	2	2	0	0	0	0	0
22	0	2	2	2	2	2	0	0	0	0	0	4	4	4	-4	-4	-3	-3	-8	-8	-8	2	2	2	2	6	0	0	0	0
21	0	0	2	2	2	-13	-13	-9	-9	-9	-9	4	4	4	-3	-3	-3	-8	-8	-8	2	2	2	2	2	6	0	0	0	0
20	0	0	2	2	2	-13	-13	-9	-9	-9	-9	4	4	4	-3	-3	-4	-8	-8	2	2	2	2	2	2	6	0	0	0	0
19	0	0	2	2	-13	-13	-9	-9	-9	-9	-9	-8	-3	-3	-3	-3	-8	-8	-8	2	-17	2	2	2	2	6	0	0	0	0
18	0	0	2	2	-1	-1	-9	-9	-9	-9	-14	0	0	0	31	31	31	-5	-8	-5	-5	-5	-5	-5	-14	6	-20	-20	0	0
17	2	2	2	2	-1	-1	-2	-2	-2	-2	-2	0	0	0	31	31	31	-5	-5	-5	-5	-5	-5	-5	-14	-14	-20	-20	0	0
16	-4	-4	-1	-1	-1	-1	-2	-2	-2	-2	-2	0	0	31	31	31	31	-5	-5	-5	-1	-1	-1	-1	-1	-1	-8	-8	0	0
15	-6	-6	-4	-1	-1	-1	0	0	0	0	-2	0	0	20	460	31	31	-5	-5	-5	-1	-1	-1	-1	-1	-1	-1	-1	0	0
14	-6	-6	0	-4	-1	0	0	0	0	0	0	20	20	20	20	59	59	3	3	3	-6	-6	-6	-6	-6	-6	-6	-6	1	1
13	0	0	0	5	5	-7	-7	-7	-7	-7	-7	20	20	20	20	59	59	3	3	3	3	-6	-6	-6	-6	-6	-6	-6	1	1
12	0	0	5	5	5	5	-7	-7	-7	-7	-7	20	20	20	20	14	14	7	3	3	3	-6	-6	6	-6	-6	-6	-6	1	1
11	0	0	0	0	5	5	-7	-7	-7	-7	-7	-11	-11	-11	-11	14	14	-2	-2	3	3	-6	-6	-6	-6	-6	-6	1	1	1
10	0	0	0	-13	-7	-7	-7	-7	-7	-7	-7	-11	-11	-11	-20	14	14	-2	-2	-2	3	-6	-6	-6	-6	-6	-6	1	1	1
9	0	0	0	-13	-7	5	5	-10	-7	-3	-11	-11	-10	-10	-5	-5	14	-2	-2	-2	3	-6	-6	-6	-6	-6	-6	1	1	1
8	0	0	0	0	3	3	3	0	-10	-3	-3	-11	1	5	-5	0	0	0	-2	-2	16	4	1	-6	-6	-6	-6	1	1	1
7	0	0	0	0	0	0	0	0	0	0	-17	-10	1	-5	-5	0	0	0	-16	-2	2	4	1	-6	-6	-6	-6	1	1	1
6	0	0	0	0	0	0	0	0	0	0	-17	-4	-4	-5	-5	12	2	2	2	2	2	-1	4	1	1	1	-6	1	1	1
5	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	8	-1	-1	-1	-1	-1	-1	4	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	7	0	0	8	8	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1
3	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	8	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(a) Year 1975

FIGURE VI-6. DIFFERENCE BETWEEN POPULATION DURING NORMAL WORKING HOURS AND TRUE RESIDENTIAL POPULATION, BY ONE-SQUARE-MILE GRID CELL. In hundreds of persons; grid numbers are listed on the left side and top of figure.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	-12	-12	-10	-10	-2	-2	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	-12	-12	-12	-12	-10	-10	-2	-2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
									BROOMFIELD																					
26	2	2	2	2	2	2	2	-9	-9	-1	-1	5	5	5	-7	-7	-7	-14	1	1	0	0	0	0	0	0	0	0	0	0
															NORTHGLENN															
25	2	2	2	2	2	2	2	-1	-1	-1	-1	5	3	5	-7	-7	-7	-14	-14	0	-12	-12	-12	0	0	0	0	0	0	0
24	2	2	2	2	2	2	-1	-1	-1	-1	-1	5	5	5	-7	-7	-18	-18	-18	-12	-12	-12	0	0	0	0	0	0	0	0
											WESTMINSTER					THORNTON														
23	0	2	2	2	2	2	-1	-1	-1	-1	-1	5	5	5	-6	-18	-18	-18	-23	-10	-10	3	3	3	3	0	0	0	0	0
														FDRL																
22	0	2	2	2	2	2	-1	-1	-1	-1	-1	5	5	5	-6	-6	-4	-4	-10	-10	-10	3	3	3	3	12	0	0	0	0
														HGTS																
21	0	0	2	2	2	-17	-17	-11	-11	-11	-11	5	5	5	-4	-4	-4	-10	-10	-10	3	3	3	3	3	12	0	0	0	0
																					RCKY MNTN ARSNL									
20	0	0	2	2	2	-17	-17	-11	-11	-11	-11	5	5	5	-4	-4	-4	-9	-9	3	3	3	3	3	3	12	0	0	0	0
									ARVADA								COMMERCE													
19	0	0	2	2	-17	-17	-11	-11	-11	-11	-11	-10	-4	-4	-4	-4	-9	-9	-9	3	-20	3	3	3	3	12	0	0	0	0
18	0	0	2	2	-1	-1	-11	-10	-11	-11	-15	7	7	7	34	34	34	-4	-9	-4	-4	-4	-4	-4	-11	12	-24	-24	0	0
17	2	2	2	2	-1	-1	-2	-2	-2	-2	-2	7	7	7	34	34	34	-4	-4	-4	-4	-4	-4	-4	-11	-11	-24	-24	0	0
								WHT. RDG												STAPL INTL										
16	-6	-6	-1	-1	-1	-1	-2	-2	-2	-2	-2	7	7	34	34	34	34	-4	-4	-4	0	0	0	0	0	0	-11	-11	0	0
		GOLDEN								EDGEWATER																				
15	-9	-9	-6	-1	-1	-1	-2	-2	-2	-2	-2	7	7	18	459	34	34	-4	-4	-4	0	0	0	0	0	0	0	0	0	0
															DENVER							AURORA								
14	-9	-9	-1	-6	-1	-2	-2	-2	-2	-2	-2	18	18	18	18	64	64	4	4	4	-9	-9	-9	-9	-9	-9	-9	-9	2	2
13	0	0	-1	7	7	-11	-11	-11	-11	-11	-11	18	18	18	18	64	64	4	4	4	4	-9	-9	-9	-9	-9	-9	-9	2	2
12	0	0	7	7	7	7	-11	-11	-11	-11	-11	18	18	18	18	24	24	-14	4	4	4	-9	-9	-9	-9	-9	-9	-9	2	2
																	GLENDALE													
11	0	0	0	0	7	7	-11	-11	-11	-11	-11	-7	-7	-7	-7	24	24	6	6	4	4	-9	-9	-9	-9	-9	-9	2	2	2
									LAKEWOOD																					
10	0	0	0	-19	-11	-11	-11	-11	-11	-11	-11	-7	-7	-7	-24	24	24	6	6	6	4	-9	-9	-9	-9	-9	-9	2	2	2
9	0	0	0	-19	-11	7	7	-14	-11	-3	-7	-7	-2	-9	-6	-6	24	6	6	6	4	-9	-9	-9	-9	-9	-9	2	2	2
			MORRISON									SHERIDAN		ENGLEWOOD																
8	0	0	0	0	4	4	4	-7	-14	-3	-3	-7	8	5	-6	2	2	2	6	6	27	9	2	-9	-9	-9	-9	2	2	2
																CHERRY HILLS														
7	0	0	0	0	0	0	-7	-7	-7	-7	-19	-2	8	-6	-6	2	2	2	-14	6	6	9	2	-9	-9	-9	-9	2	2	2
6	0	0	0	0	0	0	-7	-7	-7	-7	-19	2	2	-6	-6	15	6	6	6	6	6	2	9	2	2	2	-9	2	2	2
								JEFF CO						LITTLETON				GREENWOOD VLG												
5	0	0	0	0	0	0	-7	-7	-7	-7	-7	9	0	0	0	11	2	2	2	2	2	2	9	2	2	2	2	2	2	2
								URBAN				CLMBN VLY																		
4	0	0	0	0	0	0	-7	-7	-7	-7	-7	9	0	0	11	11	2	2	2	2	2	2	2	2	2	2	2	2	2	2
3	0	0	0	0	0	0	-7	-7	-7	-7	-7	9	0	0	0	11	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2	0	0	0	0	0	0	0	4	-7	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(b) Year 1985

FIGURE VI-6 (Continued)

```
       1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16   17   18   19   20   21   22   23   24   25   26   27   28   29   30
 30    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    1    1    1    1    0    0    0    0
 29    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    2    0    0    0    0    1    1    1    1    0    0    0    0
 28    0    0    0    0    0    0    0    0    0  -19  -19  -15  -15   -3   -3    2    2    2    2    2    2    2    1    1    1    1    0    0    0    0
 27    0    0    0    0    0    0    0  -19  -19  -19  -19  -15  -15   -3   -3    2    2    2    2    2    2    1    1    1    1    1    0    0    0    0
                                            BROOMFIELD
 26    3    3    3    3    3    3    3  -14  -14   -2   -2    6    6    6   -5   -5   -5  -14    2    2    1    1    1    1    1    1    0    0    0    0
                                                                          NORTHGLENN
 25    3    3    3    3    3    3    3   -2   -2   -2   -2    6    6    6   -8   -5   -5  -14  -14    1  -15  -15  -18    1    1    1    0    0    0    0
 24    3    3    3    3    3    3   -2   -2   -2   -2   -2    6    6    6   -5   -5  -35  -35  -35  -15  -15  -15    1    1    1    1    0    0    0    0
                                                      WESTMINSTER    THORNTON
 23    0    3    3    3    3    3   -2   -2   -2   -2   -2    6    6    6   -9  -35  -35  -35  -42  -11  -11    4    4    4    4    1    0    0    0    0
                                                                     FDRL
 22    0    3    3    3    3    3   -2   -2   -2   -2   -2    6    6    6   -9   -9   -4   -4  -11  -11  -11    4    4    4    4   19    0    0    0    0
                                                                     HGTS
 21    0    0    3    3    3  -21  -21  -13  -13  -13  -13    6    6    6   -4   -4   -4  -11  -11  -11    4    4    4    4    4   19    0    0    0    0
                                                                                                        RCKY MNTN ARSNL
 20    0    0    3    3    3  -21  -21  -13  -13  -13  -13    6    6    6   -4   -4   -1   -9   -9    4    4    4    4    4    4   19    0    0    0    0
                                            ARVADA                                   COMMERCE
 19    0    0    3    3  -21  -21  -13  -13  -13  -13  -13  -13   -4   -4   -4   -4   -9   -9   -9    4  -23    4    4    4    4   19    0    0    0    0
 18    0    0    3    3   -2   -2  -13  -10  -13  -13  -16   16   16   16   38   38   38   -3   -9   -3   -3   -3   -3   -3   -8   19  -28  -28    0    0
 17    3    3    3    3   -2   -2   -4   -4   -4   -4   -4   16   16   16   38   38   38   -3   -3   -3   -3   -3   -3   -3   -8   -8  -28  -28    0    0
                                       WHT. RDG                                                STAPL. INTL
 16   -9   -9   -2   -2   -2   -2   -4   -4   -4   -4   -4   16   16   38   38   38   38   -3   -3   -3    2    2    2    2    2    2  -18  -18    0    0
         GOLDEN                                  EDGEWATER
 15  -13  -13   -9   -2   -2   -2   -7   -7   -7   -7   -4   16   16   16  460   38   38   -3   -3   -3    2    2    2    2    2    2    2    2    0    0
                                                                          D E N V E R                        AURORA
 14  -13  -13   -2   -9   -2   -7   -7   -7   -7   -7   -7   16   16   16   16   72   72    6    6    6  -13  -13  -13  -13  -13  -13  -13  -13    4    4
 13    0    0   -2   10   10  -15  -15  -15  -15  -15  -15   16   16   16   16   72   72    6    6    6    6  -13  -13  -13  -13  -13  -13  -13    4    4
 12    0    6   10   10   10   10  -15  -15  -15  -15  -15   16   16   16   16   40   40   -9    6    6    6  -13  -13  -13  -13  -13  -13  -13    4    4
                                                                                    GLENDALE
 11    0    0    0    0   10   10  -15  -15  -15  -15  -15   -2   -2   -2   -2   40   40   21   21    6    6  -13  -13  -13  -13  -13  -13    4    4    4
                                       LAKEWOOD
 10    0    0    0  -26  -15  -15  -15  -15  -15  -15  -15   -2   -2   -2  -20   40   40   21   21   21    6  -13  -13  -13  -13  -13  -13    4    4    4
  9    0    0    0  -26  -15   10   10  -18  -15    0   -2   -2    0   -3   -4   -4   40   21   21   21    6  -13  -13  -13  -13  -13  -13    4    4    4
         MORRISON                                          SHERIDAN  ENGLEWOOD
  8    0    0    0    0    7    7    7  -17  -10    0    0   -2   15    2   -4    8    8    8   21   21   43   17    4  -13  -13  -13  -13    4    4    4
                                                                               CHERRY HILLS
  7    0    0    0    0    0    0  -17  -17  -17  -17  -21    8   15   -4   -4    8    8    8  -11   21   10   17    4  -13  -13  -13  -13    4    4    4
  6    0    0    0    0    0    0  -17  -17  -17  -17  -21   12   12   -4   -4   10   10   10   10   10   10    2   17    4    4    4  -13    4    4    4
                                       JEFF CO                  LITTLETON           GREENWOOD VLG
  5    0    0    0    0    0    0  -17  -17  -17  -17  -17   12    0    0    0    9    2    2    2    2    2    2   17    4    4    4    4    4    4    4
                                       URBAN          CLMBN VLY
  4    0    0    0    0    0    0  -17  -17  -17  -17  -17   12    0    0    9    9    2    2    2    2    2    2    2    2    4    4    4    4    4    4
  3    0    0    0    0    0    0  -17  -17  -17  -17  -17   12    0    0    0    9    2    2    2    2    2    2    2    2    4    4    4    4    4    4
  2    0    0    0    0    0    0    0    7  -17    7    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
  1    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
```

(c) Year 2000

FIGURE VI-6 (Concluded)

TABLE VI-3. OZONE DOSAGE AND EXPOSURE ESTIMATES FOR 3 AUGUST 1976 METEOROLOGY AND EMISSIONS IN GIVEN YEAR. Dosage given in 10^4 pphm-person-hours, exposure given in 10^3 person-hours.

(a) Year 1976 Emissions

TIME (MST) T1	T2	DOSAGE	EXPOSURE TO OZONE ABOVE 8. PPHM	10. PPHM	12. PPHM	14. PPHM	16. PPHM	18. PPHM	20. PPHM	22. PPHM	24. PPHM
500.	600.	23.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	700.	103.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	800.	312.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	900.	759.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1000.	1584.99	364.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1100.	2804.33	1180.10	607.56	381.50	127.18	0.00	0.00	0.00	0.00	0.00
500.	1200.	4224.20	2113.49	1365.41	990.86	470.22	192.48	0.00	0.00	0.00	0.00
500.	1300.	5533.52	2911.75	1942.28	1430.78	752.61	366.64	102.69	20.52	0.00	0.00
500.	1400.	6746.06	3553.21	2375.48	1746.45	977.35	523.51	214.87	42.03	13.40	13.40
500.	1500.	7706.83	3972.51	2585.61	1850.49	1038.60	532.60	214.87	42.03	13.40	13.40
500.	1600.	8382.72	4098.59	2658.81	1855.04	1038.60	532.60	214.87	42.03	13.40	13.40
500.	1700.	8903.70	4236.02	2669.01	1855.04	1038.60	532.60	214.87	42.03	13.40	13.40
500.	1800.	9414.47	4407.66	2689.52	1855.04	1038.60	532.60	214.87	42.03	13.40	13.40

(b) Year 1985 Emissions

TIME (MST) T1	T2	DOSAGE	EXPOSURE TO OZONE ABOVE 8. PPHM	10. PPHM	12. PPHM	14. PPHM	16. PPHM	18. PPHM	20. PPHM	22. PPHM	24. PPHM
500.	600.	21.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	700.	83.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	800.	249.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	900.	558.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1000.	1075.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1100.	1820.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1200.	2747.08	200.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1300.	3738.92	552.59	100.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1400.	4690.59	825.66	181.78	28.81	0.00	0.00	0.00	0.00	0.00	0.00
500.	1500.	5520.48	906.04	181.78	28.81	0.00	0.00	0.00	0.00	0.00	0.00
500.	1600.	6177.97	906.04	181.78	28.81	0.00	0.00	0.00	0.00	0.00	0.00
500.	1700.	6642.97	906.04	181.78	28.81	0.00	0.00	0.00	0.00	0.00	0.00
500.	1800.	7013.67	906.04	181.78	28.81	0.00	0.00	0.00	0.00	0.00	0.00

TABLE VI-3 (Concluded)

(c) Year 2000 Emissions

TIME (MST)		DOSAGE	EXPOSURE TO OZONE ABOVE								
T1	T2		8. PPHM	10. PPHM	12. PPHM	14. PPHM	16. PPHM	18. PPHM	20. PPHM	22. PPHM	24. PPHM
500.	600.	26.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	700.	103.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	800.	299.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	900.	643.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1000.	1178.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1100.	1912.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1200.	2825.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1300.	3856.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1400.	4872.54	60.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1500.	5792.97	60.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1600.	6558.38	60.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1700.	7090.76	60.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
500.	1800.	7481.00	60.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

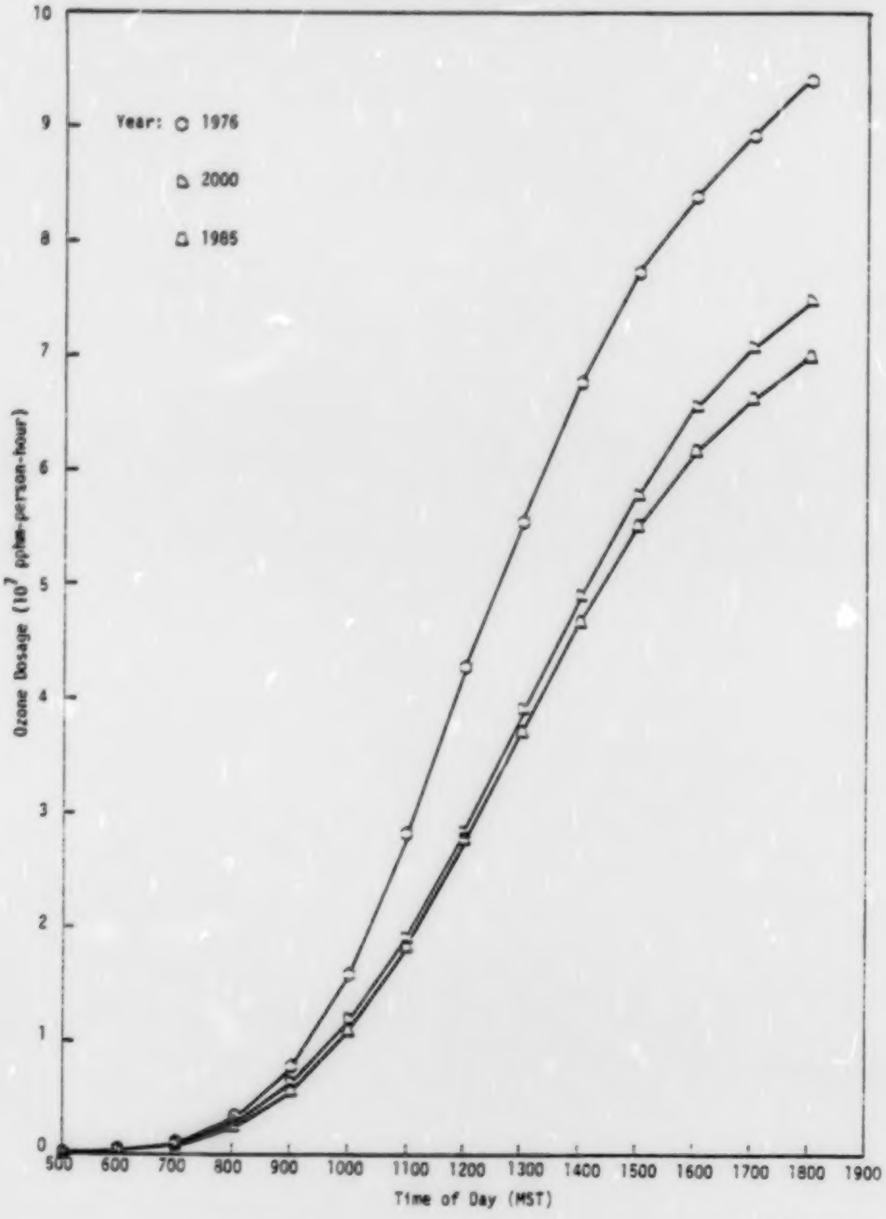


FIGURE VI-7. CUMULATIVE OZONE DOSAGE AS A FUNCTION OF TIME OF DAY FOR 3 AUGUST 1976 METEOROLOGY

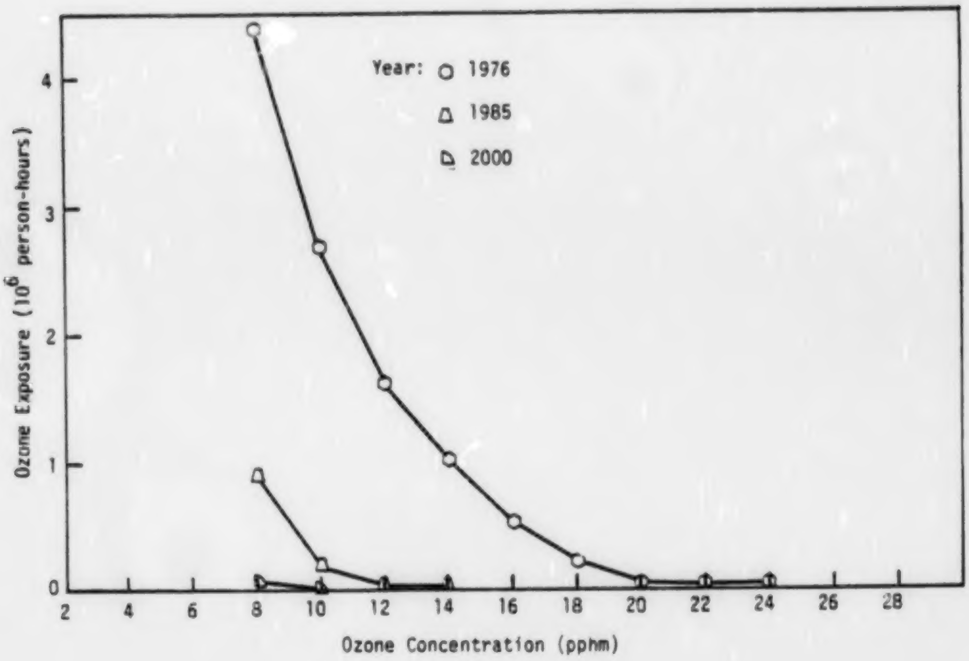


FIGURE VI-8. ESTIMATED EXPOSURE TO OZONE AS A FUNCTION OF OZONE CONCENTRATION FOR 3 AUGUST 1976 METEOROLOGY

ozone concentrations for an entire day, and the regional population. The population is expected to increase by roughly 21 percent from 1976 to 1985 and 30 percent from 1985 to 2000, so these dosage calculations show that mean ozone concentrations decrease by about 38 percent from 1976 to 1985 and another 18 percent from 1985 to 2000.

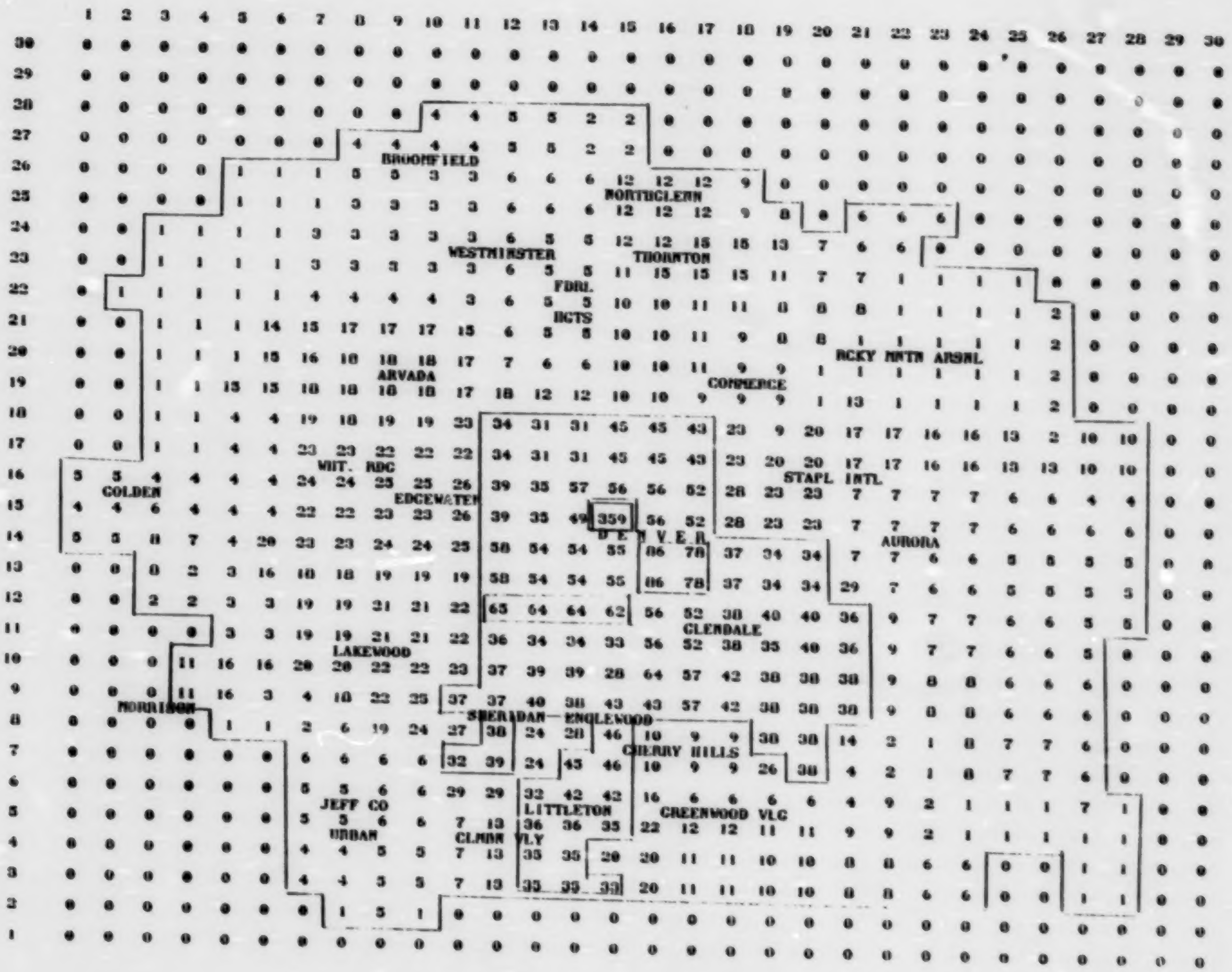
The exposure calculations reflect the great improvement in air quality obtained by a very significant reduction of the peak ozone concentrations. Table VI-3 shows that exposure to ozone concentrations above the National Ambient Air Quality Standard of 0.08 ppm for one hour drops by about 80 percent from 1976 to 1985 and a further 93 percent from 1985 to 2000.

The spatial distribution of dosage within the region for 1976, 1985, and 2000 can be seen in Figure VI-9. An examination of this figure shows that:

> The areal extent over which significant dosages occur remains roughly the same for 1976, 1985, and 2000. There is a tendency for the areal extent to increase for future years, primarily because of expansion of population outwards.
> Since the variation in daily average ozone concentration over the region is not large, the dosage patterns tend to reflect the population distribution patterns. Districts with high populations tend to have high dosages and districts with low populations experience low dosages.

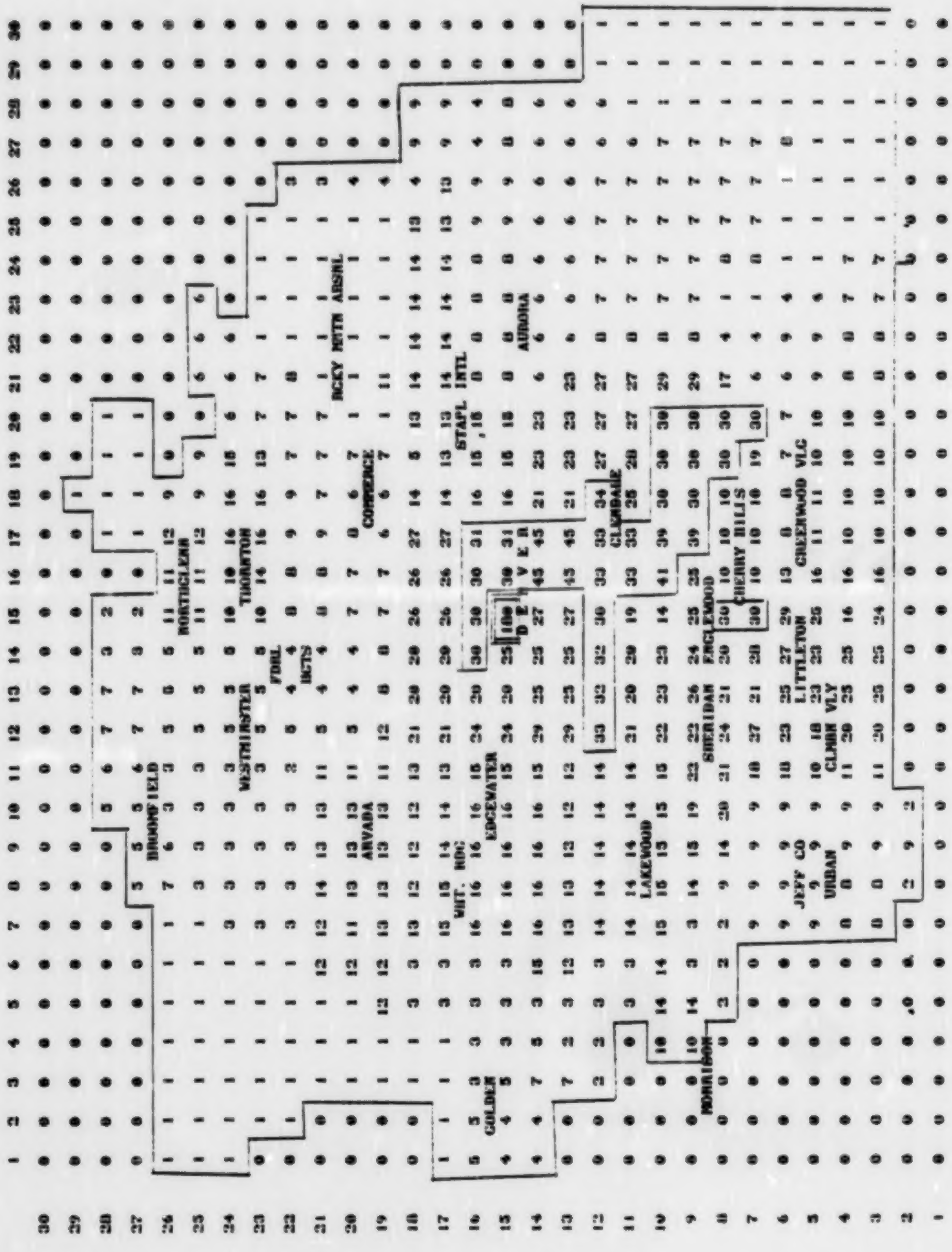
The spatial distributions of estimated exposure are presented in Figure VI-10. In contrast to dosage patterns, an examination of this figure reveals the following:

> The area in which exposure to concentrations higher than the NAAQS occurs decreases very significantly from 1976 to 1985 and again from 1985 to 2000.
> Within the affected subregions the exposure tends to reflect the population distribution.


BROOMFIELD
NORTHGLENN
WESTMINSTER
THORNTON
FDRL. HGTS
ARVADA
COMMERCE
RCKY MNTN ARSNL
WHT. RDG
EDGEWATER
STAPL INTL.
GOLDEN
DENVER
AURORA
GLENDALE
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
JEFF CO URBAN
LITTLETON
GREENWOOD VLG
CLMBN VLY

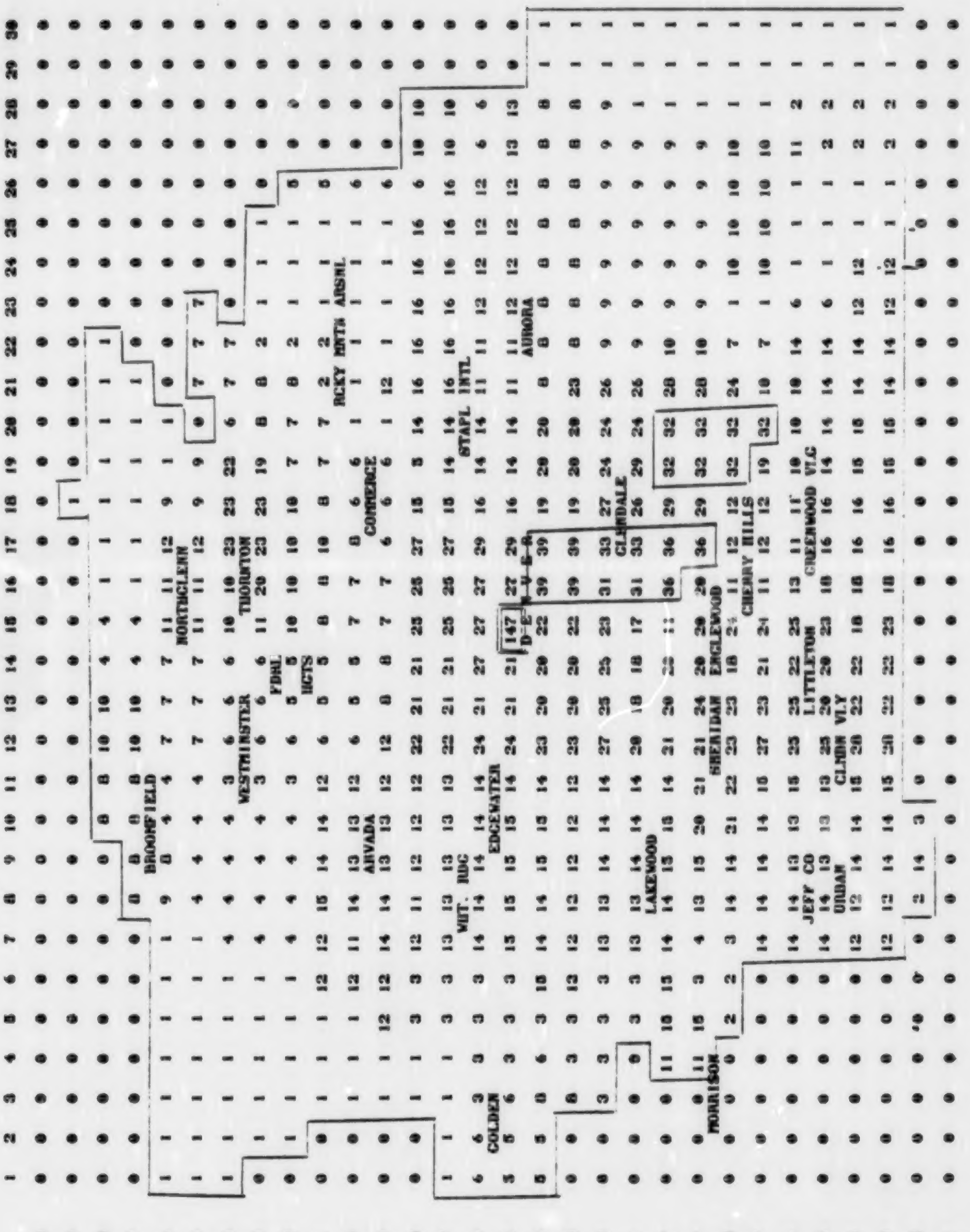
(a) Year 1976 Emissions

FIGURE VI-9. CUMULATIVE OZONE DOSAGES (IN 10^6 PPHM-PERSON-HOURS) IN ONE-SQUARE-MILE GRID CELLS FROM 500 TO 1800 HOURS (MST) FOR 3 AUGUST 1976 METEOROLOGY AND EMISSIONS IN GIVEN YEAR. Grid numbers are listed on the left side and top of the figure.


BROOMFIELD
NORTHGLENN
WESTMINSTER
THORNTON
FDHL HGTS
ARVADA
WHT. RDG
EDGEWATER
GOLDEN
D E N V E R
COMMERCE
RCKY MNTN ARSNL
STAPL INTL
AURORA
GLENDALE
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
LITTLETON
CLMBN VLY
GREENWOOD VLG
JEFF CO URBAN

(b) Year 1985 Emissions

FIGURE VI-9 (Continued)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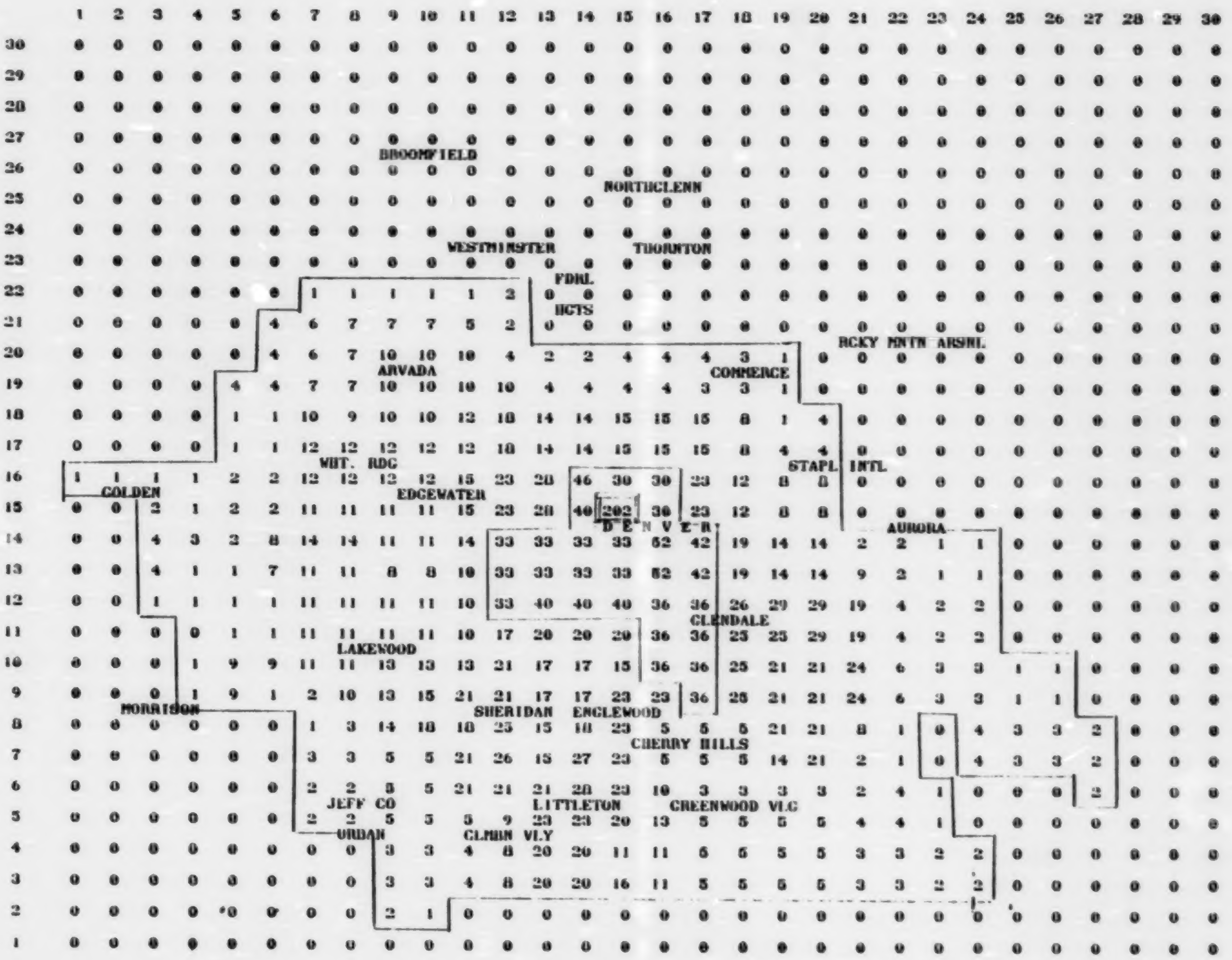
NORTHGLENN
WESTMINSTER
THORNTON
FDRL HGTS
ARVADA
RCKY MNTN ARSNL
COMMERCE
WHT. RDG
EDGEWATER
GOLDEN
STAPL INTL
AURORA
147
D-E-N-V-E-R
GLENDALE
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
LITTLETON
GREENWOOD VLG
JEFF CO
URBAN
CLMBN VLY

(c) Year 2000 Emissions

FIGURE VI-9 (Concluded)


BROOMFIELD
NORTHGLENN
WESTMINSTER
THORNTON
FDRL
HGTS
RCKY MNTN ARSNL
ARVADA
COMMERCE
WHT. RDG
STAPL INTL
GOLDEN
EDGEWATER
D E N V E R
AURORA
GLENDALE
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
JEFF CO
LITTLETON
GREENWOOD VLG
URBAN
CLMBN VLY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	1	1	1	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	4	6	7	7	7	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	4	6	7	10	10	10	4	2	2	4	4	4	3	1	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	4	4	7	7	10	10	10	10	4	4	4	4	3	3	1	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	1	1	10	9	10	10	12	18	14	14	15	15	15	8	1	4	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	1	1	12	12	12	12	12	18	14	14	15	15	15	8	4	4	0	0	0	0	0	0	0	0	0	0
16	1	1	1	1	2	2	12	12	12	12	15	23	28	46	30	30	23	12	8	8	0	0	0	0	0	0	0	0	0	0
15	0	0	2	1	2	2	11	11	11	11	15	23	28	40	202	30	23	12	8	8	0	0	0	0	0	0	0	0	0	0
14	0	0	4	3	2	8	14	14	11	11	14	33	33	33	33	62	42	19	14	14	2	2	1	1	0	0	0	0	0	0
13	0	0	4	1	1	7	11	11	8	8	10	33	33	33	33	62	42	19	14	14	9	2	1	1	0	0	0	0	0	0
12	0	0	1	1	1	1	11	11	11	11	10	33	40	40	40	36	36	26	29	29	19	4	2	2	0	0	0	0	0	0
11	0	0	0	0	1	1	11	11	11	11	10	17	20	20	20	36	36	25	25	29	19	4	2	2	0	0	0	0	0	0
10	0	0	0	1	9	9	11	11	13	13	13	21	17	17	15	36	36	25	21	21	24	6	3	3	1	1	0	0	0	0
9	0	0	0	1	9	1	2	10	13	15	21	21	17	17	23	23	36	25	21	21	24	6	3	3	1	1	0	0	0	0
8	0	0	0	0	0	0	1	3	14	18	18	25	15	18	23	5	5	5	21	21	8	1	0	4	3	3	2	0	0	0
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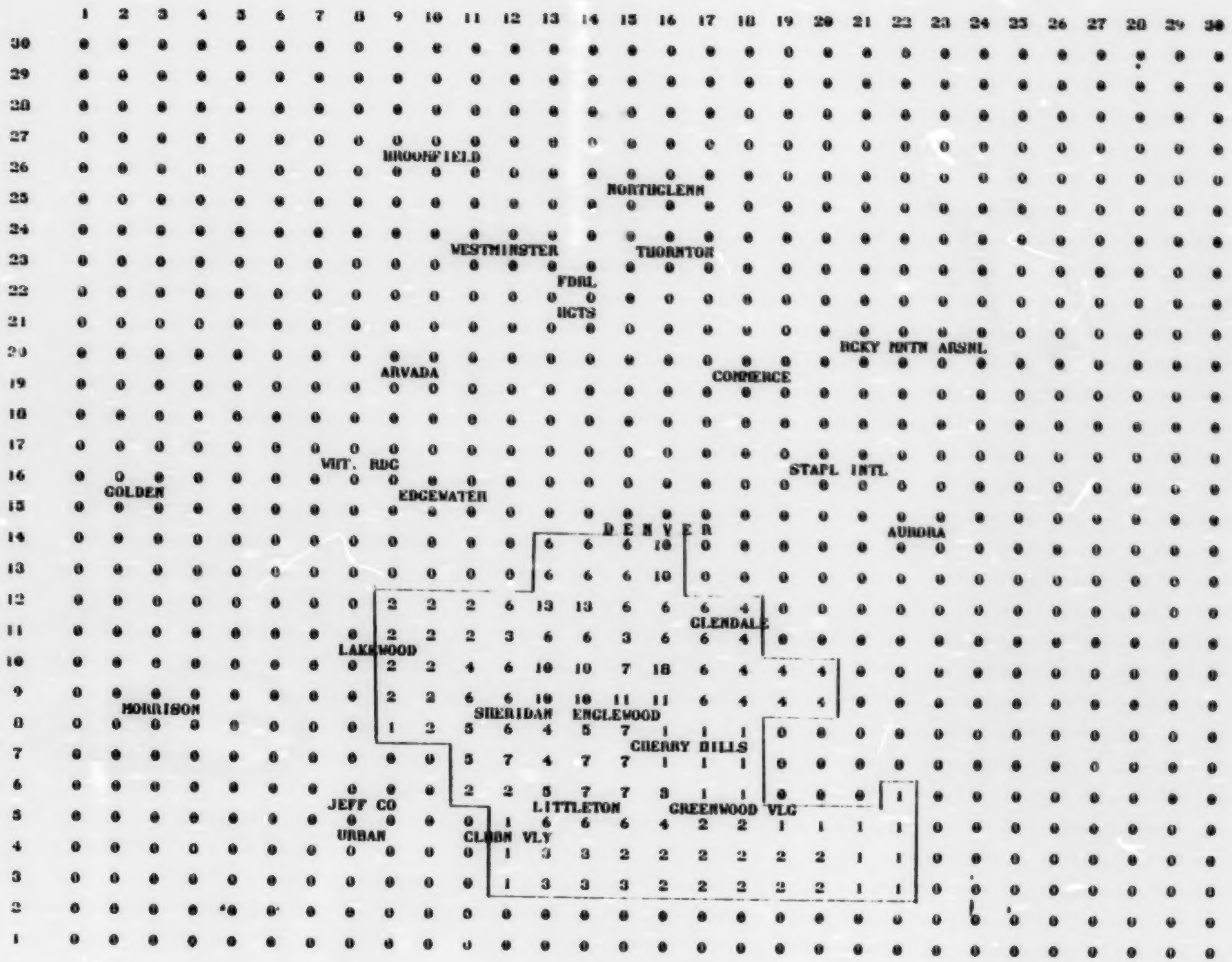
3	0	0	0	0	0	0	0	0	3	3	4	8	20	20	16	11	5	5	5	5	3	3	2	2	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

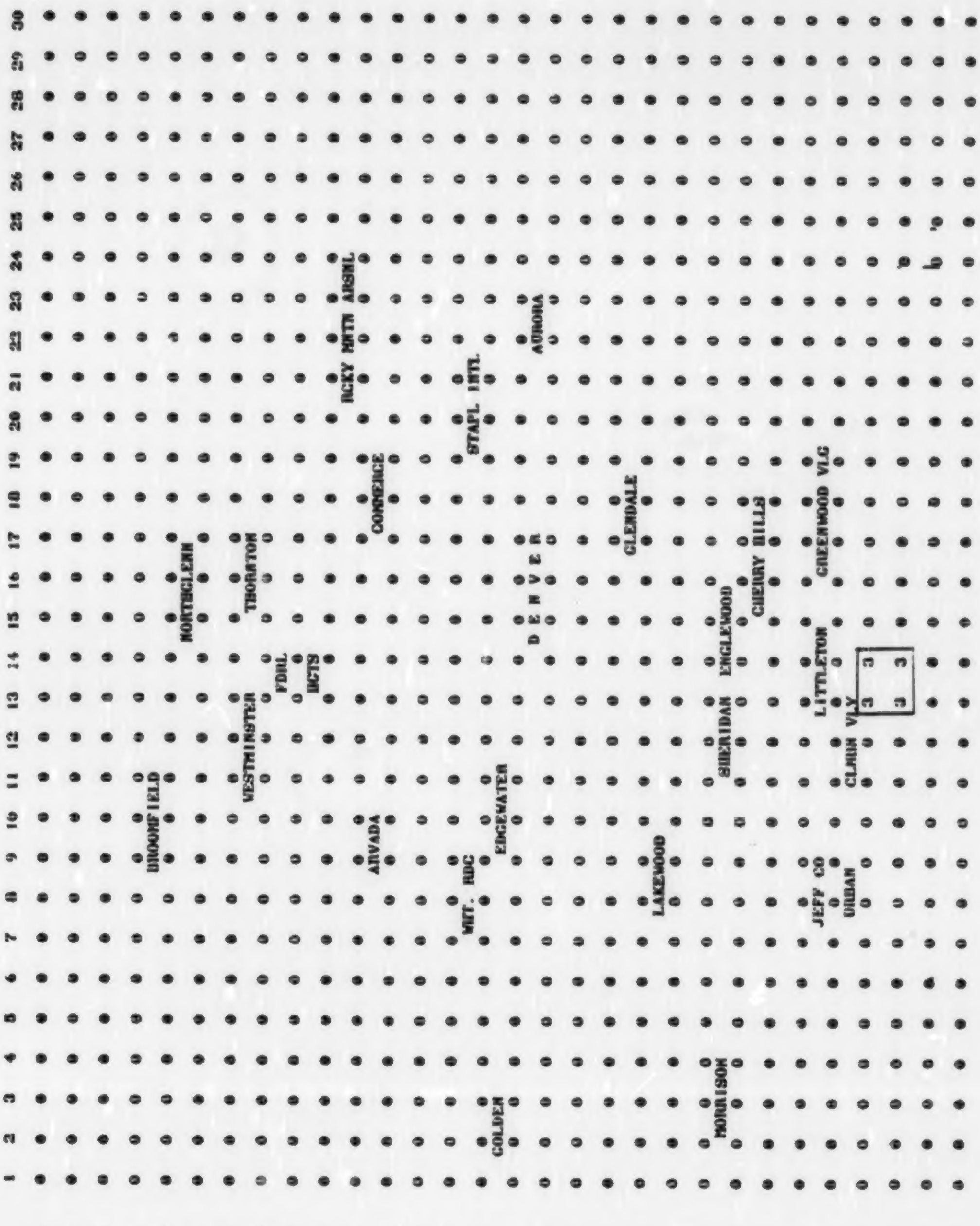
(a) Concentration Greater than 8 pphm; Year 1976 Emissions

FIGURE VI-10. CUMULATIVE EXPOSURE (IN 10^3 PERSON-HOURS) TO OZONE CONCENTRATIONS ABOVE GIVEN LEVEL IN ONE-SQUARE-MILE GRID CELLS BETWEEN 500 AND 1800 HOURS FOR 3 AUGUST 1976 METEOROLOGY AND GIVEN YEAR EMISSIONS. Grid numbers are listed on left side and top of figure.


BROOMFIELD
NORTHGLENN
WESTMINSTER
THORNTON
FDRL
HGTS
RCKY MNTN ARSNL
ARVADA
COMMERCE
WHT. RDG
STAPL INTL
GOLDEN
EDGEWATER
D E N V E R
AURORA
GLENDALE
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
JEFF CO
URBAN
LITTLETON
GREENWOOD VLG
CLRDN VLY

(b) Concentration Greater than 16 pphm; Year 1976 Emissions

FIGURE VI-10 (Continued)


1
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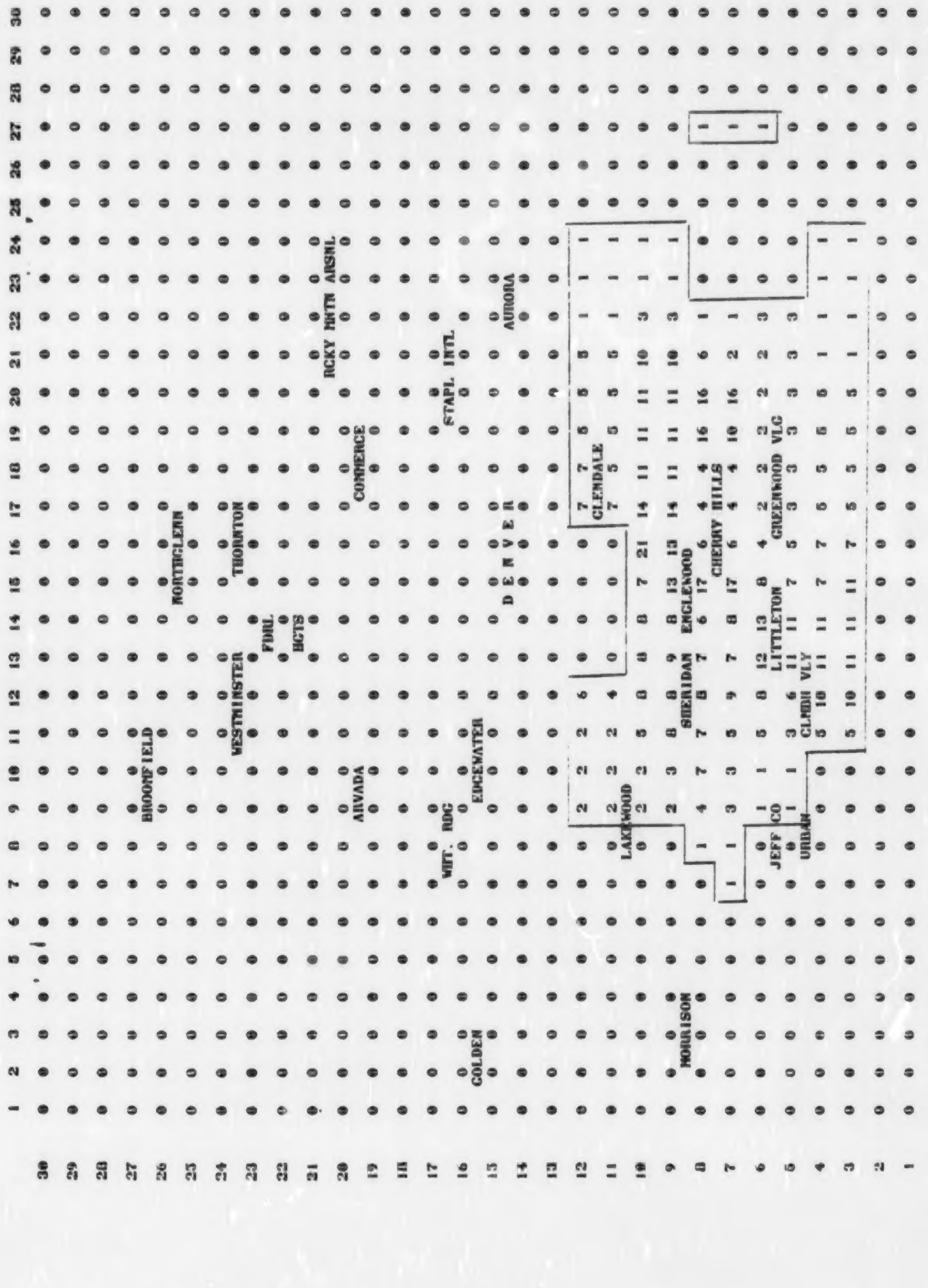
29
30
BROOMFIELD
NORTHGLENN
THORNTON
WESTMINSTER
FDRL HGTS
ARVADA
COMMERCE
RCKY MNTN ARSNL
STAPL INTL
AURORA
D E N V E R
GLENDALE
WHT. RDG
EDGEWATER
GOLDEN
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
GREENWOOD VLG
LITTLETON
CLMBN VLY
JEFF CO
URBAN
3
3
3
3

(c) Concentration Greater than 24 pphm; Year 1976 Emissions

FIGURE VI-10 (Continued)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THORNTON
WESTMINSTER
FDRL HGTS
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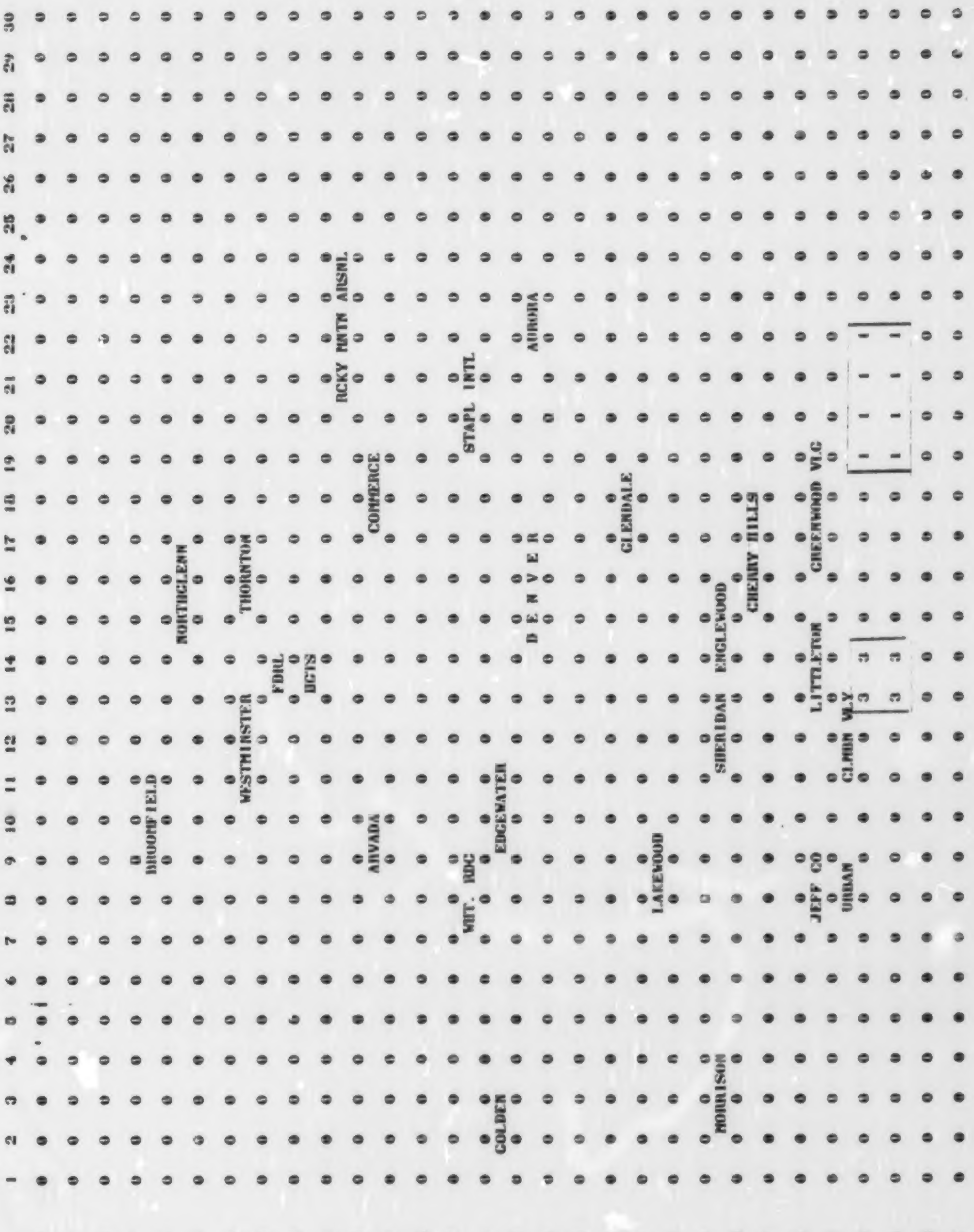
COMMERCE
STAPL INTL
AURORA
D E N V E R
GLENDALE
ARVADA
WHT. RDG
EDGEWATER
GOLDEN
MORRISON
LAKEWOOD
SHERIDAN
ENGLEWOOD
CHERRY HILLS
LITTLETON
GREENWOOD VLG
CLMBN VLY
JEFF CO
URBAN

(d) Concentration Greater than 8 pphm; Year 1985 Emissions

FIGURE VI-10 (Continued)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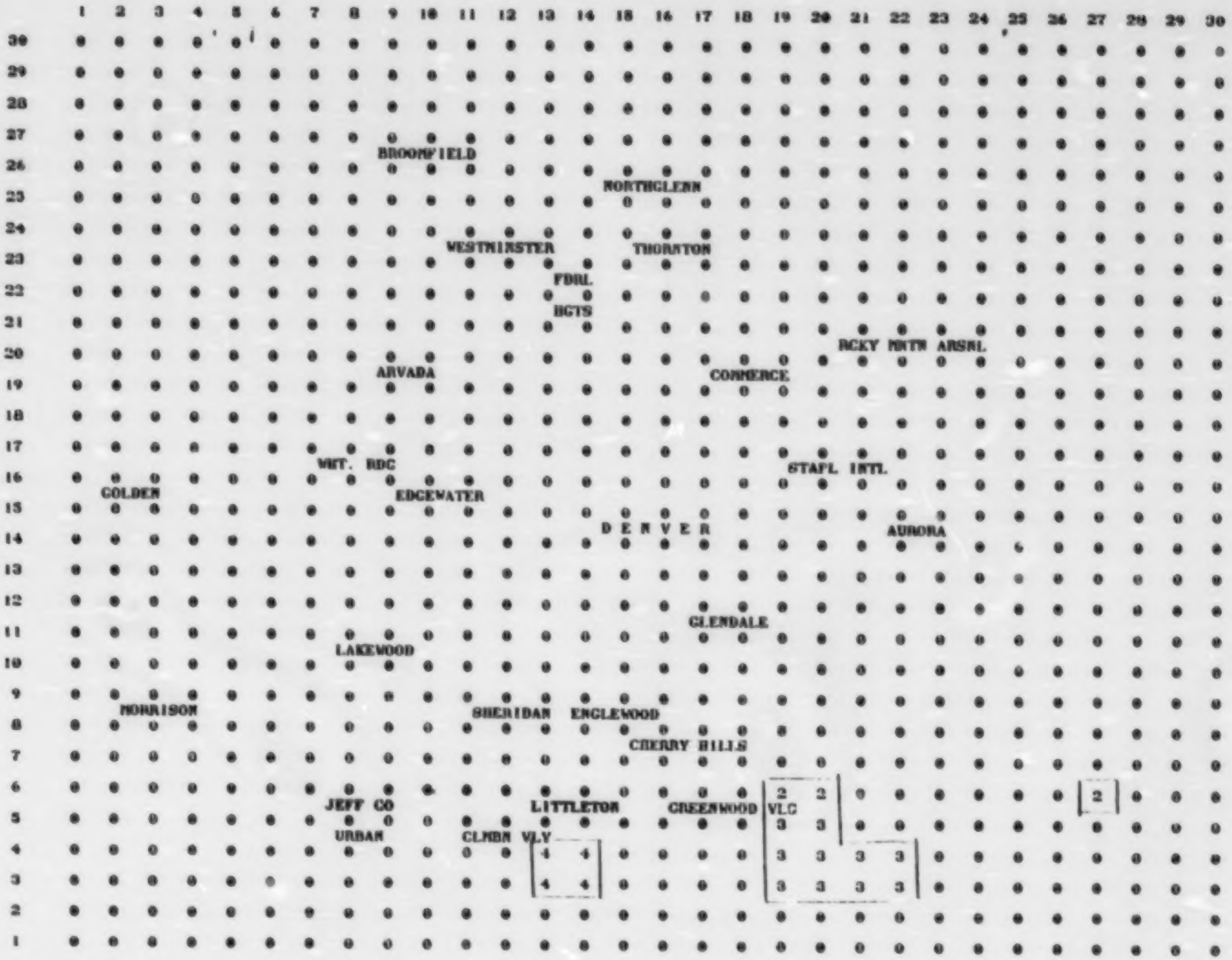
ARVADA
RCKY MNTN ARSNL
COMMERCE
STAPL INTL
AURORA
DENVER
GLENDALE
WHT. RDG
EDGEWATER
GOLDEN
LAKEWOOD
SHERIDAN
ENGLEWOOD
CHERRY HILLS
MORRISON
LITTLETON
GREENWOOD VLG
JEFF CO URBAN
CLMBN VLY

(e) Concentration Greater than 12 pphm; Year 1985 Emissions

FIGURE VI-10 (Continued)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NORTHGLENN
WESTMINSTER
THORNTON
FDRL
HGTS
RCKY MNTN ARSNL
ARVADA
COMMERCE
WHT. RDC
STAPL INTL
GOLDEN
EDGEWATER
D E N V E R
AURORA
GLENDALE
LAKEWOOD
MORRISON
SHERIDAN
ENGLEWOOD
CHERRY HILLS
JEFF CO
URBAN
LITTLETON
GREENWOOD
VLG
CLMBN VLY
2
3
4

(f) Concentration Greater than 8 pphm; Year 2000 Emissions

FIGURE VI-10 (Concluded)

Since not all areas will have ozone concentrations exceeding the NAAQS, there appear to be sharp boundaries to the regions where significant exposure occurs, and these boundaries are defined by the boundaries of the ozone cloud rather than by the population distributions. Note that the area in which ozone concentrations exceed the NAAQS not only shrinks in size but moves southward away from the high population concentration in central Denver. The latter is a major contributor to the sharp decrease in exposure for future years.

E. SUMMARY AND CONCLUSIONS

Dosages and exposures to ozone were estimated for the Denver metropolitan region for three years--1975, 1985, and 2000. The ozone concentrations were obtained from the SAI Denver Model simulations of 3 August 1976 meteorology and 1976, 1985, and 2000 emissions. The population distribution was obtained from the Sub-area Allocation Plan and was adjusted to account for a shift in the population during working hours.

Dosages tend to reflect a general reduction in the ambient ozone concentration over the entire day. The estimated dosages showed a 25 percent drop from 1975 to 1985 but a 6.5 percent increase from 1985 to 2000. When discounted for the increases in population between these years, the dosages reflect an effective reduction in ambient ozone by 38 percent from 1975 to 1985 and 18 percent from 1985 to 2000.

Exposure is a measure of the impact of relatively brief but high ozone concentrations. Exposure to ozone about the NAAQS is projected to decrease 80 percent from 1976 to 1985 and another 93 percent from 1985 to 2000. These results are biased because for the 3 August 1976 meteorology used here the peak ozone concentrations are located south of central Denver and away from the regions of high population. Peak ozone concentrations may occur over central Denver on other days, and in such a case the improvement in exposure levels for future years may not be as great as that obtained here.

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APPENDIX A

DESCRIPTION OF THE MODELS

APPENDIX A

DESCRIPTION OF THE MODELS

by James P. Killus

Urban airshed models are mathematical representations of atmospheric transport and chemical reaction processes which, when combined with a source emissions inventory and appropriate meteorological data, may be used to predict pollutant concentrations as a function of time and location in an airshed. In the past several years, SAI has developed a number of airshed models for specific research and applications tasks. Depending upon the application, these models differ in the importance given to selected physical and chemical phenomena, but all have certain features in common:

> A modeling region, divided into a number of horizontal and vertical cells, and boundary conditions that define the concentrations of pollutants in air entering the modeling region from the top and sides.

> A source inventory which defines the emissions of pollutants into each cell of the modeling region.

> A meteorological file which determines the advective transport of pollutants within the region, and a diffusivity algorithm which provides the rate of vertical diffusion of pollutants.

> A kinetic mechanism to predict the changes in pollutant concentrations resulting from chemical reactions (for those modeling applications involving chemically reactive species).

In the next sections we discuss the Denver Air Quality Model and its treatment of each of the above factors. The appendix closes with a much briefer description of the well-known Climatological Dispersion Model (CDM) also used in this study.

The Denver Air Quality Model--called simply the "Denver Model" here--is an adaptation of several airshed models previously developed at SAI.* The starting point was the airshed model developed for the California ARB (Liu et al., 1976a) to treat the advection and diffusion of SO_2 (or any linear species) from power plant plumes. The model used SHASTA numerics, and had the capability of treating winds (Reynolds et al., 1977) with vertical variations. Because of its modular nature, this model was relatively easy to modify in order to include:

- Treatment of 12 chemical species (the Carbon-Bond kinetic mechanism).
- A diffusivity algorithm developed specifically to aid in the treatment of the onset of radiative inversions.
- An inversion breakup algorithm.
- Various input-output codes designed to facilitate treatment of the grid conventions used by the Colorado Department of Highways.

1. THE MODELING REGION AND BOUNDARY CONDITIONS

The modeling region chosen was a 30 x 30 mile grid bounded at the bottom by the ground and extending to the top of the mixing layer (or 2500 ft., whichever is less). Although it would be desirable to extend the modeling region some distance into the inversion, for various reasons--including a lack of pollutant measurements aloft--this extension is not yet within our modeling capabilities.

The 30 x 30 mile region was chosen for the original CDH study in an attempt to place the boundaries in areas where pollutant concentrations in air flowing into the region could be expected to be near background levels. The boundaries chosen are well beyond the areas of substantial emissions;

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* The Colorado Department of Highways (CDH, 1976) used one of these models, the Air Pollution Simulation Program (APSP), in an analysis of the I-470 Highway proposal. The APSP differs from the Denver Model in some important respects, notably the kinetic mechanism employed. The CDH/APSP simulations gave markedly different results from the present study. Factors that we discuss at some length below led us to the conclusion that the ASPS is inappropriate for use in the Denver area, hence our decision to develop the Denver Model.

presumption of "clean" boundary inflows was thus quite acceptable except when some of the pollutants that had been blown out of the modeling region might have reentered it when the wind reversed. This possibility could not be investigated in the present project because the region in question (south of Denver) has uneven terrain and no data are available for characterizing its wind field.

The 30 x 30 mile modeling region was divided horizontally into a 15 x 15 set of grid cells, with three stacked layers in the vertical direction. This reduction from the 30 x 30 x 5 cell modeling grid used in the CDH/APSP study was made in the interest of reducing computing costs; the Denver Model requires roughly four times the computing time of the ASPS for a given simulation, owing to the doubling of the number of chemical species. Several tests were made to see if the reduction in spatial resolution would affect predictions. It was found that the results from a 15 x 15 cell modeling region were nearly identical to an averaging of the results from a 30 x 30 cell region. The change from five to three vertical layers results in somewhat faster mixing, since each cell is assumed to be a well-mixed box. However, this effect is minor because of the rapidity of vertical diffusion in the Denver region.

2. THE EMISSIONS INVENTORY*

The starting point in preparing an emissions inventory suitable for the Denver Model is the Emissions Data Preparation Program (EDPP) developed by Reynolds (1973) for SAI's original APSP. The inputs to the EDPP include:

- > Auto vehicle miles traveled (VMT) along major thoroughfares (in link node format).
- > Auto area sources (traffic on side streets, etc.).
- > Small point sources (industrial emissions, house heating, etc.).

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* A full description of the emissions data used in this project is given in Appendix B.

The output from the EDPP is a six species emissions inventory--NO, NO_2, CO, reactive HC, unreactive hydrocarbons and a blank file for O_3 (since O_3 is not a primary pollutant). The reactive hydrocarbon inventory of the EDPP was then divided between the four categories required by the Carbon-Bond mechanism. The assumed split was, by weight, 0.032 olefins, 0.65 paraffins, 0.05 aldehydes, and 0.205 aromatics (Reynolds et al., 1977); the remainder was assumed to be unreactive and was disregarded, along with the unreactive hydrocarbon emissions inventory in the EDPP. The resulting inventory of the emissions of each of eight species in the 30 x 30 grid was block-averaged into the 15 x 15 grid used in the Denver Model. Blank files for HNO_2, H_2O_2, peroxyacetylnitrate (PAN), and aerosols were also added. Emissions from large point sources such as power plants were input directly to the model at elevated locations, corresponding to risen chimney plumes.

3. THE METEOROLOGICAL FILE AND DIFFUSIVITY ALGORITHM

The meteorological file used in the Denver Model is also a modification of files prepared for the APSP. The Meteorological Data Preparation Program (MDPP) interpolates surface wind measurements to generate a two-dimensional wind field. The Denver Model requires input of a three-dimensional wind field. Lacking both data aloft and the time for a detailed theoretical estimation of winds aloft, in this project we simply extended the MDPP surface winds aloft, effectively rendering the three-dimensional wind feature of the Denver Model inoperative.

It is worthy of note that there is evidence of a breakup of the inversion layer in Denver around midday on the days for which data were available. (If there were no inversion present, the top of the modeling region could not be the inversion base.) Under these circumstances we chose to treat transport and dispersion explicitly in a limited modeling region 2500 ft. high. At the top, pollutants are allowed to slowly leak out of the modeling region at a rate based upon atmospheric diffusivities and the concentration gradient within the region.

The vertical diffusivity algorithm used in this study (Liu et al., 1976b) was developed for application to Las Vegas, Nevada. This algorithm was specifically developed to treat radiative inversions; communication with the CDH suggested that the Lamb algorithm used in the CDH/APSP (Lamb et al., 1975) had some difficulties in handling the onset of radiative inversions. Comparison of the two algorithms suggests that the Liu algorithm provides a better treatment of stable atmospheric conditions, particularly at the onset of radiative stability, while the Lamb algorithm is more accurate in its treatment of unstable conditions. However, since the two algorithms yield only minor differences in model predictions under unstable conditions (particularly with only three vertical modeling layers) but yield very different results under stable conditions, we felt that the Liu algorithm was preferable for this project.

We described above the features of the Denver Model that pertain to emissions and atmospheric transport. In simplest terms, an airshed model of reactive pollutants consists of three coupled mechanisms: emissions, transport, and chemical reactions. Emissions and transport (meteorology) are inputs to the SAI model. These processes are straightforward; our ability to account for them is restricted primarily by the data available to us.

4. TREATMENT OF CHEMICAL REACTIONS

The photochemistry of urban smog is not as well understood. The reactions known or postulated to occur in photochemical smog number in the many hundreds. The number of reactions actually taking place is probably many times that. Our ability to model the ozone formation process rests upon the construction of various lumped kinetic schemes that approximate the more complex reality.

A chemical kinetic mechanism is therefore the most critical feature of a photochemical airshed model. There are some general considerations important in developing such a mechanism. First, the mathematical description of the mechanism (in terms of the number of species included) must not be overly complex, or else computation times for the model within which it is embedded are likely to be excessive. On the other hand, an overly simplified mechanism may omit important reaction steps and thus be inadequate to describe atmospheric reactions over a range of conditions. A major requirement, then, is that the mechanism include only a limited degree of detail, yet still predict the chemical behavior of a complex mixture of organic and inorganic species. In particular, accurate prediction of the formation of ozone is of prime importance, since ozone is the major constituent of photochemical oxidant and has the largest data base for validation purposes.

In general, development of chemical kinetic mechanisms has three stages: (1) laboratory experiments designed to elucidate specific chemical reaction steps, their rate constants, and their products, (2) smog chamber studies based upon rather simple analogs to the complex atmospheric mixture, and (3) atmospheric studies, either fixed ground-level observations of a changing air mass or airborne studies that attempt to follow a single air mass (Calvert, 1976a, 1976b). The specific reaction steps proposed at the first stage are linked together into a specific mechanism (written for the photooxidation of a specific hydrocarbon), which is validated against the smog chamber studies in the second stage. These specific mechanisms are often quite complex, e.g., the Whitten and Hogo (1977) mechanism for propylene contains 65 reactions. Any attempt to prepare and link together specific mechanisms for each of the hydrocarbon species in smog would be computationally intractable even if sufficient theoretical backing for such a mechanism existed.

Instead, the insight gained in comparisons with smog chamber data is condensed into a generalized lumped mechanism with the hydrocarbon species grouped into one or more categories whose average behavior is then represented by a single set of reactions for each species. Lumped mechanisms are validated against both smog chamber data and, when coupled with a transport model (either an airshed or trajectory model), atmospheric data.

Tables A-1 through A-3 list the reactions used in the Hecht-Seinfeld (1972), Hecht-Seinfeld-Dodge (Hecht et al., 1974a), and the original formulation of the Carbon-Bond (Whitten and Hogo, 1977) mechanisms. These mechanisms were developed by SAI under EPA auspices in attempts to incorporate state-of-the-art chemistry into a computationally efficient mechanism. Each successive mechanism represents what we believe to be a major advance over the previous mechanism. In the case of the Hecht-Seinfeld mechanism, at least, subsequent advances (principally the addition of aldehyde chemistry) have rendered it obsolete. This is conclusively demonstrated by the present project, which represents the first side-by-side comparison of different kinetic mechanisms applied to the atmosphere.

The Carbon-Bond mechanism represents an advance over the Hecht-Seinfeld-Dodge mechanism that is more subtle than the difference between the H-S and H-S-D mechanisms. In addition to realistic aromatic chemistry, the Carbon-Bond mechanism offers an improved lumping scheme, mass-conservative hydrocarbon depletion, and an elimination of sensitive stoichiometric parameters. The Carbon-Bond mechanism therefore requires less tuning and is more user-oriented than the H-S-D mechanism.

The test of any simulation model is two-fold: (1) Does it obey the requirements of accepted scientific theory? (2) Are its predictions in acceptable agreement with observations? Below, we present the basic details of atmospheric photochemistry as they apply to ozone formation in photochemical smog and a discursive comparison of the utility of the H-S, H-S-D, and C-B mechanisms. We then consider the predictions of the Denver Model in comparison with the observed air quality in Denver.

a. Urban Airshed Photochemistry and Its Simulation by Lumped Kinetic Mechanisms

Ozone and other oxidants are formed within the troposphere primarily by the chemical interaction of nitrogen oxides and hydrocarbons. This

TABLE A-1. THE HECHT-SEINFELD MECHANISM

$$NO_2 + h\nu \xrightarrow{1} NO + O$$

$$O + O_2 + M \xrightarrow{2} O_3 + M$$

$$O_3 + NO \xrightarrow{3} NO_2 + O_2$$

$$O_3 + NO_2 \xrightarrow{4} NO_3 + O_2$$

$$NO_3 + NO_2 \xrightarrow[H_2O]{5} 2\ HNO_3$$

$$NO + NO_2 \xrightarrow[H_2O]{6} 2\ HNO_2$$

$$HNO_2 + h\nu \xrightarrow{7} OH + NO$$

$$CO + OH \xrightarrow[O_2]{8} CO_2 + HO_2$$

$$HO_2 + NO \xrightarrow{9} OH + NO_2$$

$$HO_2 + NO_2 \xrightarrow{10} HNO_2 + O_2$$

$$HC + O \xrightarrow{11} \alpha RO_2$$

$$HC + OH \xrightarrow{12} \beta RO_2$$

$$HC + O_3 \xrightarrow{13} \gamma RO_2$$

$$RO_2 + NO \xrightarrow{14} NO_2 + \varepsilon OH$$

$$RO_2 + NO_2 \xrightarrow{15} PAN$$

Source: Hecht (1972).

TABLE A-2. THE HECHT-SEINFELD-DODGE MECHANISM

$$\left.\begin{aligned} NO_2 + h\nu &\xrightarrow{1} NO + O \\ O + O_2 + M &\xrightarrow{2} O_3 + M \\ O_3 + NO &\xrightarrow{3} NO_2 + O_2 \end{aligned}\right\}\text{The } NO_2\text{-}NO\text{-}O_3 \text{ Cycle}$$

$$\left.\begin{aligned} O + NO + M &\xrightarrow{4} NO_2 + M \\ O + NO_2 &\xrightarrow{5} NO + O_2 \\ O + NO_2 + M &\xrightarrow{6} NO_3 + M \end{aligned}\right\}\begin{array}{l}\text{Important Reactions of O} \\ \text{with Inorganic Species}\end{array}$$

$$\left.\begin{aligned} O_3 + NO_2 &\xrightarrow{7} NO_3 + O_2 \\ NO_3 + NO &\xrightarrow{8} 2NO_2 \\ NO_3 + NO_2 &\xrightarrow{9} N_2O_5 \\ N_2O_5 &\xrightarrow{10} NO_2 + NO_3 \\ N_2O_5 + H_2O &\xrightarrow{11} 2HNO_3 \end{aligned}\right\}\begin{array}{l}\text{The Chemistry of } NO_3, \\ N_2O_5, \text{ and } HNO_3\end{array}$$

$$\left.\begin{aligned} NO + HNO_3 &\xrightarrow{12} HNO_2 + NO_2 \\ HNO_2 + HNO_3 &\xrightarrow{13} H_2O + 2NO_2 \end{aligned}\right\}\begin{array}{l}\text{Reactions of } HNO_3 \text{ with} \\ \text{Inorganic Species}\end{array}$$

$$\left.\begin{aligned} NO + NO_2 + H_2O &\xrightarrow{14} 2HNO_2 \\ 2HNO_2 &\xrightarrow{15} NO + NO_2 + H_2O \\ HNO_2 + h\nu &\xrightarrow{16} OH + NO \end{aligned}\right\}\text{Chemistry of } HNO_2$$

TABLE A-2 (Continued)

$$\left.\begin{array}{rcl} OH + NO_2 & \xrightarrow{17} & HNO_3 \\ OH + NO + M & \xrightarrow{18} & HNO_2 + M \\ OH + CO + (O_2) & \xrightarrow{19} & CO_2 + HO_2 \end{array}\right\} \begin{array}{l}\text{Important Reactions of} \\ \text{OH with Inorganic Species}\end{array}$$

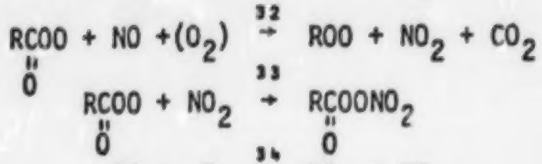
$$\left.\begin{array}{rcl} HO_2 + NO & \xrightarrow{20} & OH + NO_2 \end{array}\right\} \text{Oxidation of NO by } HO_2$$

$$\left.\begin{array}{rcl} H_2O_2 + h\nu & \xrightarrow{21} & 2OH \end{array}\right\} \text{Photolysis of } H_2O_2$$

$$\left.\begin{array}{rcl} HC_1 + O & \xrightarrow{22} & ROO + \alpha R\underset{\overset{\|}{O}}{C}OO + (1-\alpha)HO_2 \\ HC_1 + O_3 & \xrightarrow{23} & R\underset{\overset{\|}{O}}{C}OO + RO + HC_4 \\ HC_1 + OH & \xrightarrow{24} & ROO + HC_4 \\ HC_2 + O & \xrightarrow{25} & ROO + OH \\ HC_2 + OH & \xrightarrow{26} & ROO + H_2O \\ HC_3 + O & \xrightarrow{27} & ROO + OH \\ HC_3 + OH & \xrightarrow{28} & ROO + H_2O \\ HC_4 + h\nu & \xrightarrow{29} & \beta ROO + (2-\beta)HO_2 \\ HC_4 + OH & \xrightarrow{30} & \beta R\underset{\overset{\|}{O}}{C}OO + (1-\beta)HO_2 + H_2O \end{array}\right\} \begin{array}{l}\text{Organic Oxidation Reactions} \\ \quad HC_1 = \text{Olefins} \\ \quad HC_2 = \text{Aromatics} \\ \quad HC_3 = \text{Paraffins} \\ \quad HC_4 = \text{Aldehydes}\end{array}$$

TABLE A-2 (Concluded)

$$\mathrm{ROO + NO \xrightarrow{31} RO + NO_2}$$



$$\mathrm{R\underset{\overset{\|}{O}}{C}OO + NO + (O_2) \xrightarrow{32} ROO + NO_2 + CO_2}$$

$$\mathrm{R\underset{\overset{\|}{O}}{C}OO + NO_2 \xrightarrow{33} R\underset{\overset{\|}{O}}{C}OONO_2}$$

$$\mathrm{RO + O_2 \xrightarrow{34} HO_2 + HC_4}$$

$$\mathrm{RO + NO_2 \xrightarrow{35} RONO_2}$$

$$\mathrm{RO + NO \xrightarrow{36} RONO}$$

Reactions of Organic Free Radicals with NO, NO_2, and O_2

$$\mathrm{HO_2 + HO_2 \xrightarrow{37} H_2O_2 + O_2}$$

$$\mathrm{HO_2 + ROO \xrightarrow{38} RO + OH + O_2}$$

$$\mathrm{2ROO \xrightarrow{39} 2RO + O_2}$$

Other Peroxy Radical Reactions

Source: Hecht et al. (1974a).

TABLE A-3. THE ORIGINAL FORMULATION OF THE CARBON-BOND MECHANISM

Reaction	Rate Constant (ppm^{-1} min^{-1})
$NO_2 + h\nu \rightarrow NO + O\cdot$	k_1^*
$O\cdot + O_2(+ M) \rightarrow O_3\ (+ M)$	2.08×10^{-5}
$O_3 + NO \rightarrow NO_2 + O_2$	25.2
$O\cdot + NO_2 \rightarrow NO + O_2$	1.34×10^4
$O_3 + NO_2 \rightarrow NO_3 + O_2$	5×10^{-2}
$NO_3 + NO \rightarrow NO_2 + NO_2$	1.3×10^4
$NO_3 + NO_2 + H_2O \rightarrow 2HNO_3$	$1.66 \times 10^{-3\dagger}$
$NO + NO_2 + H_2O \rightarrow 2HNO_2$	$2.2 \times 10^{-9\dagger}$
$HNO_2 + h\nu \rightarrow NO + OH$	$k^*_{HNO_2}$
$NO_2 + OH\cdot \rightarrow HNO_3$	9×10^3
$NO + OH\cdot \rightarrow HNO_2$	9×10^3
$CO + OH\cdot \rightarrow CO_2 + HO_2$	2.06×10^2
$OLE + OH\cdot \xrightarrow{O_2} HCHO + CH_3O_2$	3.8×10^4
$PAR + OH\cdot \xrightarrow{O_2} CH_3O_2 + H_2O$	1.3×10^3
$ARO + OH\cdot \xrightarrow{O_2} HCHO + CH_3O_2$	8×10^3
$OLE + O\cdot \xrightarrow{2O_2} HC(O)O_2\cdot + CH_3O_2$	5.3×10^3
$PAR + O\cdot \xrightarrow{O_2} CH_3O_2\cdot + OH\cdot$	20
$ARO + O\cdot \xrightarrow{2O_2} HC(O)O_2 + CH_3O_2$	37
$OLE + O_3 \xrightarrow{O_2} HC(O)O_2 + HCHO + OH\cdot$	0.01

TABLE A-3 (Concluded)

Reaction	Rate Constant ($ppm^{-1}min^{-1}$)
$ARO + O_3 \xrightarrow{O_2} HC(O)O_2 + HCHO + OH\cdot$	0.002
$OLE + O_3 \rightarrow$ ozonide	0.005
$HCHO + h\nu \xrightarrow{2O_2} HC(O)O_2 + HO_2$	$k^*_{HCHO \rightarrow radicals}$
$HCHO + h\nu \rightarrow CO + H_2$	$k^*_{HCHO \rightarrow CO}$
$HCHO + OH\cdot \xrightarrow{O_2} HC(O)O_2 + H_2O$	1×10^4
$HO_2 + NO \rightarrow OH\cdot + NO_2$	2×10^3
$CH_3O_2 + NO \rightarrow NO_2 + HCHO + HO_2$	2×10^3
$HC(O)O_2 + NO \rightarrow NO_2 + CO_2 + HO_2$	2×10^3
$H_2O_2 + h\nu \rightarrow OH\cdot + OH\cdot$	$k^*_{H_2O_2}$
$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$	4×10^3
$CH_3O_2^{!} + HO_2 \rightarrow H_3COOH + O_2$	4×10^3
$HC(O)O_2^{\cdot} + HO_2 \rightarrow HC(O)OOH + O_2$	1×10^4
$HC(O)O_2 + NO_2 \rightarrow PAN$	150
$PAN \rightarrow HC(O)O_2^{\cdot} + NO_2$	0.02
$ARO + NO_3 \rightarrow PRODUCTS$	50
$HO_2 + NO_2 \rightarrow HNO_2$	20.

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* Photolysis rate constants in units of min^{-1}.

† Units of $ppm^{-2}min^{-1}$.

Source: Whitten and Hogo (1977).

interaction is driven by ultraviolet radiation from the sun. The nitrogen oxides and hydrocarbons, the precursors for oxidant formation, are emitted from both natural and anthropogenic sources. Their concentrations and the intensity of solar ultraviolet radiation are affected by meteorological phenomena.

The interactions between pollutants that lead to ozone (oxidant) formation are complex and nonlinear. However, many years of research have established certain basic interactions, which are divided into three areas for this discussion:

> Inorganic chemistry--the interactions between nitrogen compounds and oxygen compounds.
> Organic oxidation chemistry--the primary paths by which hydrocarbons and their oxygenated intermediates participate in ozone (oxidant) formation.
> Induction effects--the sources of radicals that can start the chain reactions involved in ozone (oxidant) formation.

1) Inorganic Chemistry of Nitrogen and Oxygen Compounds

Ozone, the major oxidant in photochemical smog, is formed when oxygen atoms react with oxygen molecules in the presence of a third body (usually a nitrogen molecule or another oxygen molecule):

$$O + O_2 + M \rightarrow O_3 + M \quad . \qquad \text{(A-1)}$$

The major source of oxygen atoms in the troposphere is the photolysis of nitrogen dioxide:

$$NO_2 + h\nu \rightarrow NO + O \quad , \qquad \text{(A-2)}$$

where $h\nu$ represents the energy of a photon of light at the frequency ν. The quantum yield for this reaction, or the percentage of absorptions of a photon that result in photolysis, is near unity for UV light with a wavelength of 400 nm (nanometers) or less. The quantum yield decreases at higher wavelengths and is near zero at 430 nm. The rate of photolysis depends on the number of photons, or the intensity of the light, and on the concentration of NO_2.

The following reaction:

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad \text{(A-3)}$$

completes an ozone production and destruction cycle. In the troposphere, Reaction (A-2) yields an oxygen atom that generates ozone by Reaction (A-1). However, Reaction (A-2) also generates an NO molecule that can combine with ozone by Reaction (A-3) to regenerate a molecule of NO_2. These three reactions are quite rapid; thus NO, NO_2, and O_3 are usually near the equilibrium relationship given by:

$$k_2[NO_2] = k_3[NO][O_3] \quad . \qquad \text{(A-4)}$$

Equation (A-4) is usually a good approximation (within 10 percent) of the actual concentrations of those species in the atmosphere.

Clearly, the above reactions will result in no net ozone production and buildup. High ozone concentrations in the troposphere are the result of the introduction of hydrocarbons into the NO_x/O_3 cycle.

2) Organic Oxidation Chemistry

So far, the reactions of only oxygen and nitrogen compounds have been discussed. If water vapor and hydrocarbons are included, however, additional species--such as HO·, and $HO_2^{\cdot}$, alkylperoxy radicals ($RO_2^{\cdot}$), $HONO_2$, and HONO--are formed from the interactions between H_2O, NO_x, and the hydrocarbons. The most important reaction involving these species is:

$$HO_2^{\cdot} + NO \rightarrow HO\cdot + NO_2 \quad . \qquad \text{(A-5)}$$

Hydroxyl radicals (HO·) resulting from Reaction (A-5) are the main radicals that begin the oxidation of organic compounds. A reaction related to Reaction (A-5) involves alkylperoxy radicals:

$$RO_2^{\cdot} + NO \rightarrow RO\cdot + NO_2 \quad , \qquad \text{(A-6)}$$

where R is an organic radical such as methyl ($CH_3^{\cdot}$) or ethyl ($CH_3CH_2^{\cdot}$). Reactions (A-5) and (A-6) convert NO to NO_2. Rewriting equation (A-4) as

$$O_3 = \frac{k_2[NO_2]}{k_3[NO]} \quad , \qquad \text{(A-7)}$$

we see that an NO to NO_2 conversion raises the steady-state concentration of ozone. Early in the smog formation process, while there is still a low NO_2 to NO ratio, the efficiency of ozone production from NO to NO_2 conversions is very low. During this period, known as the induction period, any ozone formed tends to rereact with the abundant NO available to form NO_2. It is only after most of the NO has been oxidized to NO_2 that the efficiency of ozone production rises. After the induction period, when the NO_2/NO ratio is high, practically every NO to NO_2 conversion results in the production of an ozone molecule. The ability of organic compounds to supply peroxy radicals for the conversion of NO to NO_2 by Reactions (A-5) and (A-6) is their most important role in the production of photochemical oxidant. The rate at which the peroxy radicals are produced depends on the reactivity of the hydrocarbons.

Thus, the basic ozone production cycle may be outlined as follows. Hydroxyl radicals (HO·) react with organic compounds (hydrocarbons, oxygenated hydrocarbons such as aldehydes, and so on) in a series of reactions to produce peroxy radicals. These peroxy radicals ($RO_2^{\cdot}$ and $HO_2^{\cdot}$) convert NO to NO_2 by Reactions (A-5) and (A-6) and regenerate the hydroxyl radicals by Reaction (A-5). When the sun is shining, the ozone concentration increases as the NO_2/NO ratio increases, as shown in the steady-state relationship of Eq. (A-7).

Support for this outline comes from numerous research studies (Niki et al., 1972; Demerjian et al., 1974; Hecht et al., 1974a; Nicolet, 1975; Calvert and McQuigg, 1975; Chameides and Walker, 1976). The relative unimportance of water vapor in photochemical oxidant production, for example, was shown by Demerjian et al. (1974). They performed a computer simulation of addition of water vapor to a system containing "clean" air, 0.1 ppm NO, and no NO_2. They found that water vapor had almost no effect on ozone production. In contrast, water vapor is important in polluted atmospheres, but within the normal dew point range its concentration is not limiting to the kinetic mechanism and therefore is not discussed here. The same workers studied the effects of carbon monoxide, which is found in both polluted and unpolluted air. Carbon monoxide was once thought to be relatively unreactive but is now known to enter into the chemistry of photochemical smog by the following reactions:

$$HO\cdot + CO \rightarrow CO_2 + H\cdot \quad , \qquad (A\text{-}8)$$

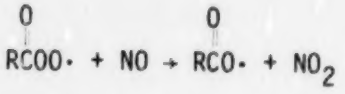
$$H\cdot + O_2 \rightarrow HO_2^{\cdot} \quad , \qquad (A\text{-}9)$$

$$HO_2^{\cdot} + NO \rightarrow HO\cdot + NO_2 \quad . \qquad (A\text{-}5)$$

Since HO· radicals are destroyed in Reaction (A-8) and produced in Reaction (A-9), the above sequence provides a chain reaction whereby a single HO· radical could initiate the oxidation of many NO molecules. To see the effect of this mechanism, Demerjian et al. (1974) added 10 ppm of CO to the computer simulation described above. After irradiation for eight hours, the "clean" air, H_2O, NO, CO atmosphere "produced" over 0.04 ppm of ozone, an increase of more than a factor of 100 over the "clean" air, H_2O, and NO system. The importance of carbon monoxide in smog formation is limited, however, by the low rate constant for Reaction (A-8) as shown by Hampson and Garvin (1975). In actual polluted atmospheres, the conversion of NO to NO_2 by oxygenated hydrocarbons and other intermediate species found in photochemical smog is so rapid that the effect of CO is obscured.

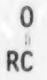
Hundreds of hydrocarbons have been identified in the urban atmosphere, yet only a few of them have been studied in detail. The discussion here is therefore limited to those classes of reactions that are currently thought to be important. As mentioned above, the main contribution of organics is to oxidize NO to NO_2 through reactions with peroxy radicals, both peroxyalkyl ($RO_2^{\cdot}$) and peroxyacyl ($RCO_3^{\cdot}$), where R is hydrogen or part of a hydrocarbon molecule. These reactions are written in the general form:

$$RO_2^{\cdot} + NO \rightarrow RO\cdot + NO_2 \quad , \qquad (A\text{-}6)$$



$$R\overset{O}{\overset{\|}{C}}OO\cdot + NO \rightarrow R\overset{O}{\overset{\|}{C}}O\cdot + NO_2 \quad . \qquad (A\text{-}10)$$

The peroxyalkyl radical is formed when the alkyl radical, R·, reacts with an oxygen molecule. Alkyl radicals are formed at various stages when paraffins, olefins, or aromatics are oxidized in the smog mechanism. The peroxyacyl radical is produced by a similar reaction scheme via the acyl radical,



$$R\overset{O}{\overset{\|}{C}} \quad ,$$

that is usually formed when an aldehyde, RCHO, is oxidized. Aldehydes are introduced directly into the atmosphere from auto exhaust and other combustion sources and are also formed as intermediates in photochemically active atmospheres. Computer simulations done by many workers indicate that the hydroxyl radical, HO·, is the dominant species that attacks hydrocarbons to form alkyl and acyl radicals (Niki et al., 1972; Demerjian et al., 1974; Hecht et al., 1974a; Nicolet, 1975; Calvert and McQuigg, 1975; Chameides and Walker, 1976).

The high rates of NO oxidation and subsequent ozone production found in photochemical smog have been accounted for by a reaction chain that begins with a hydrocarbon being attacked by an hydroxyl radical. The peroxy radical formed then oxidizes NO, and HO· is eventually regenerated. This sequence can be summarized by the following set of reactions:

$$\mathrm{RH + OH\cdot \rightarrow R\cdot + H_2O} \quad , \tag{A-11}$$

$$\mathrm{R\cdot + O_2 \rightarrow RO_2^{\cdot}} \quad , \tag{A-12}$$

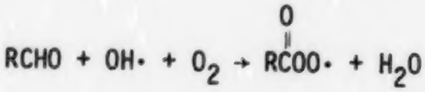
$$\mathrm{RO_2^{\cdot} + NO \rightarrow RO\cdot + NO_2} \quad , \tag{A-6}$$

$$\mathrm{RO\cdot + O_2 \rightarrow R'CHO + HO_2^{\cdot}} \quad , \tag{A-13}$$

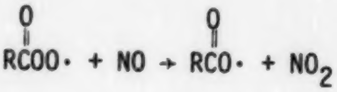
$$\mathrm{RO\cdot \rightarrow HCHO + R'^{\cdot}} \tag{A-14}$$

$$\mathrm{HO_2^{\cdot} + NO \rightarrow OH\cdot + NO_2} \quad , \tag{A-5}$$

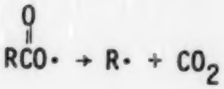
and for aldehydes:



$$\mathrm{RCHO + OH\cdot + O_2 \rightarrow R\overset{\overset{O}{\|}}{C}OO\cdot + H_2O} \quad , \tag{A-15}$$



$$\mathrm{R\overset{\overset{O}{\|}}{C}OO\cdot + NO \rightarrow R\overset{\overset{O}{\|}}{C}O\cdot + NO_2} \quad , \tag{A-10}$$

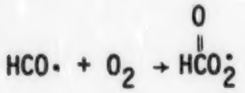


$$\mathrm{R\overset{\overset{O}{\|}}{C}O\cdot \rightarrow R\cdot + CO_2} \quad , \tag{A-16}$$

followed by Reactions (A-12), (A-6), (A-13), and (A-5). These are two HO· cycles wherein HO· starts the cycle and is returned at the end of the cycle. The first cycle results in two NO molecules being oxidized to NO_2 with the concomitant reduction of one carbon atom from the organic (RH). The second cycle results in three NO molecules oxidized when the organic is an aldehyde. The HO· cycles are terminated when two free radicals combine. This overall process is responsible for converting NO molecules to NO_2 and converting the reactive hydrocarbons to CO_2 and H_2O. Note that aldehydes resulting from Reactions (A-13) and (A-14) can react by (A-15), (A-10), and other reactions. Aldehydes can also photolyze and bring more radicals into the system:

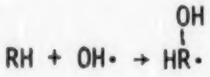
$$RCHO + h\nu \rightarrow HCO\cdot + R\cdot \quad , \qquad (A\text{-}17)$$

$$HCO\cdot + O_2 \rightarrow CO + HO_2^{\cdot} \quad , \qquad (A\text{-}18)$$



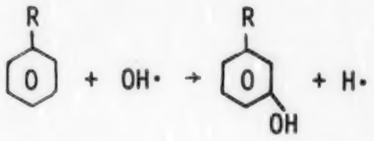
$$HCO\cdot + O_2 \rightarrow H\overset{\overset{O}{\|}}{C}O_2^{\cdot} \quad . \qquad (A\text{-}19)$$

The number of NO molecules converted in the original two cycles is complicated by Reaction (A-17) followed by either (A-18) or (A-19). The two ratios of the rate constants of Reactions (A-13) to (A-14) and (A-18) to (A-19) are not currently known with certainty (Demerjian et al., 1974). It can also be shown that reactions like (A-11) can proceed by addition:



$$RH + OH\cdot \rightarrow H\overset{\overset{OH}{|}}{R}\cdot$$

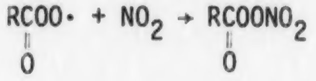
with the series of reactions beginning with Reaction (A-12), producing similar results. For substituted aromatic compounds, another type of reaction may occur:



(A-20)

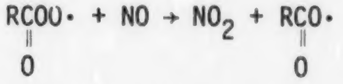
The ultimate fate of aromatic compounds in smog chemistry is not certain at the present time, however. For example, the number of NO conversions per cycle when the aromatic ring eventually breaks open is not known. The reaction scheme [Reactions (A-6) and (A-10) through (A-19)] does, however, include the dominant organic reactions that convert NO to NO_2, which is the major step required to raise the ozone concentration (via the steady-state relationship). Many other different organic species and inorganic intermediate species are also formed in photochemical smog (Demerjian et al., 1974, pp. 65-108). Although the reactions involving these species are not well understood at this time, it is expected that their effect is only to modify and not substantially change the results predicted with regard to O_3 production using only the simplified reaction scheme described above.

Explanation of the formation of complex organic molecules requires that some additional reactions be considered. The most important of these compounds are the PAN (peroxyacetyl nitrate) types that cause eye irritation and were first discovered in the Los Angeles atmosphere. PAN-type compounds are formed from the reaction between the peroxyacyl radicals and NO_2:



$$R\underset{\underset{O}{\|}}{C}OO\cdot + NO_2 \rightarrow R\underset{\underset{O}{\|}}{C}OONO_2 \quad . \qquad \text{(A-21)}$$

This reaction competes with Reaction (A-22):



$$R\underset{\underset{O}{\|}}{C}OO\cdot + NO \rightarrow NO_2 + R\underset{\underset{O}{\|}}{C}O\cdot \quad . \qquad \text{(A-22)}$$

Reaction (A-21) will dominate when the NO_2/NO ratio is high.

3) Induction Effects

As previously noted, before ozone can begin to form and accumulate rapidly, a sizable fraction of precursor NO must be oxidized to NO_2 (90 to 99 percent of NO_x emissions are initially in the form of NO). The time required for this initial oxidation is called the induction period.

In order to explain the formation of photochemical smog it is necessary that there be a source of radicals sufficient to build and maintain a radical concentration many times greater than that found in clean air. At such concentrations, the induction period is shortened to a few hours and ozone production proceeds efficiently during the hours of brightest sunlight.

The hydroxyl radicals that play an important part in the mechanism to convert NO to NO_2 are, as discussed above, regenerated at various stages in the mechanism, but the source of the hydroxyl radicals, an important issue, was not discussed. Virtually any type of radical can initiate the oxidant-producing mechanism by means of radical transfer reactions. For example, Reaction (A-5) transforms peroxy radicals to hydroxyl radicals.

Maintaining the total concentration of radicals in the mechanism by carbonyl photolysis is necessary because of the numerous temporary and permanent radical sinks. For example, both nitrous acid and hydrogen peroxide are temporary radical sinks because they are formed rapidly via reactions that consume radicals:

$$OH\cdot + NO \rightarrow HNO_2 \quad , \tag{A-23}$$

$$HO_2^{\cdot} + HO_2^{\cdot} \rightarrow H_2O_2 \quad . \tag{A-24}$$

However, both species can reproduce radicals at a later time by photolysis. The most important permanent radical sink also appears to be the most important sink of oxides of nitrogen:

$$HO\cdot + NO \rightarrow HONO \quad . \tag{A-25}$$

Other radical sinks include reaction with surfaces and various radical-radical reactions:

$$RO_2 + RO_2 \rightarrow RO + RO \quad .$$

Some early investigators thought that oxygen atoms from NO_2 photolysis might be the source of radicals that initiate the mechanism of ozone formation (Leighton, 1961). However, more recent work has shown this radical source to be insufficient in explaining the high radical concentrations in photochemical smog (Hecht, et al., 1974b).

Because most reactions that generate radicals are photolysis reactions, the intensity of sunlight affects the induction period. However, slight variations in trace quantities of nitrous acid, HNO_2, (Chan et al., 1976) or aldehydes can easily be shown to affect induction time strongly (Calvert and McQuigg, 1975), which suggests that either of these substances could be the source of initial radicals.

In smog chambers, the photolysis of nitrous acid,

$$HNO_2 + h\nu \rightarrow HO\cdot + NO \quad , \qquad \text{(A-26)}$$

may be the most important initial source of radicals. Nitrous acid has been detected in smog chambers in concentrations sufficient to explain the observed induction time for smog chemistry, but the concentrations necessary to initiate smog chemistry in the atmosphere are below the limits of measurement of most modern instruments.

Nitrous acid is produced in the absence of sunlight:

$$NO + NO_2 + H_2O \rightarrow HNO_2 + HNO_2 \quad . \qquad \text{(A-27)}$$

This reaction proceeds rapidly on some surfaces and may also proceed slowly in the gas phase (Calvert and McQuigg, 1975). High local concentrations of the three reactants could lead to nitrous acid formation in the real atmosphere, but the importance of this reaction is not known at present (Chan et al., 1976). Since nitrous acid is produced in photochemical smog by Reaction (A-23), some nitrous acid might persist to initiate radicals and then smog formation on a subsequent day. Ripperton et al. (1975) and Smith et al. (1976) have suggested that the presence of these radicals may be responsible for increased ozone formation on the second day.

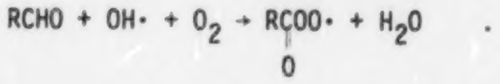
Aldehyde photolysis is critical in maintaining the radical concentration in smog because it is a primary pollutant and it is also generated from other hydrocarbons in the photochemical process

[Reaction (A-14)]. Furthermore, the formation of an aldehyde does not result in the net subtraction of any radicals from the radical pool as does the formation of HNO_2 and H_2O_2.

Aldehydes are, however, very difficult to treat in atmospheric models. Emissions data concerning aldehydes are largely lacking and there are few atmospheric measurements of aldehydes. Aldehydes are also difficult to treat in kinetic mechanisms, owing to the variety of their reaction pathways--photolysis that produces radicals [Reaction (A-13)], photolysis that does not produce radicals [Reaction (A-28)], and reaction with hydroxyl radicals [Reaction (A-15)] which leads to oxidation of the carbonyl without net production of radicals:

$$RCHO + h\nu \rightarrow HCO\cdot + R\cdot \qquad (A-13)$$

$$RCHO + h\nu \rightarrow RH + CO \qquad (A-28)$$



$$RCHO + OH\cdot + O_2 \rightarrow R\underset{\overset{\|}{O}}{C}OO\cdot + H_2O \quad . \qquad (A-15)$$

Recognition of the crucial role of aldehydes in smog chemistry is a recent development; early attempts to devise photochemical kinetic mechanisms omitted aldehydes, (Eschenroeder and Martinez, 1972; Wayne et al., 1971; Hecht and Seinfeld, 1972). These mechanisms could be made to approximate the simplified behavior of a smog chamber. However, they predict unrealistic behavior in the atmosphere, although this fact has until recently been masked by the complex behavior of the urban airshed models. In the next section, we discuss the inadequacies of the kinetic mechanism in the APSP, and our reasons for choosing a more up-to-date mechanism for the Denver Model.

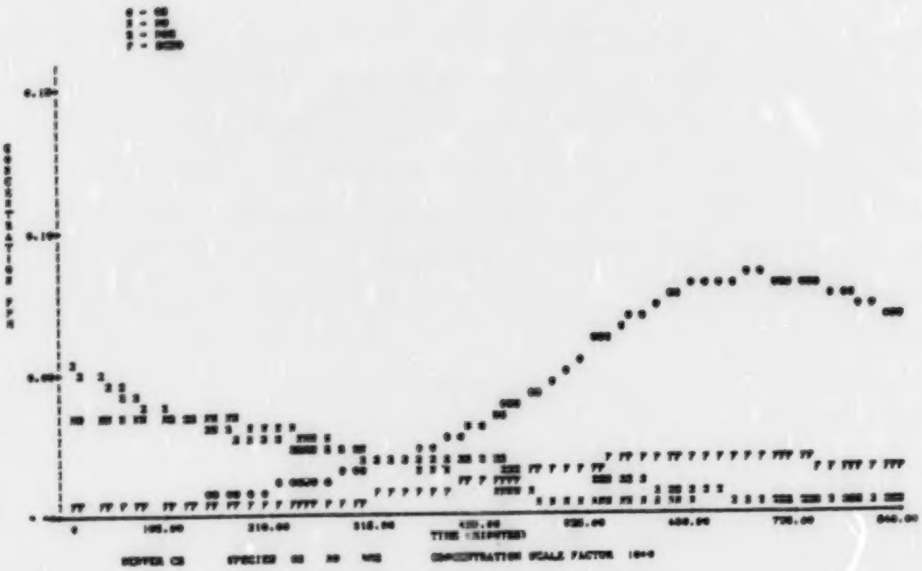
b. Critique of the APSP Incorporating the Hecht-Seinfeld Kinetic Mechanism

The original airshed model developed by SAI in 1972, the first photochemical airshed model, was recognized at the time as a first-generation effort. It was anticipated that subsequent research and development would expand the base of knowledge and allow advances in model conception and execution. The H-S kinetic mechanism in that model reflected a knowledge of smog chemistry that was sketchy, but the best available at that time. We will now consider that mechanism in light of present knowledge to support the need for new formulations that adequately model realistic atmospheric situations.

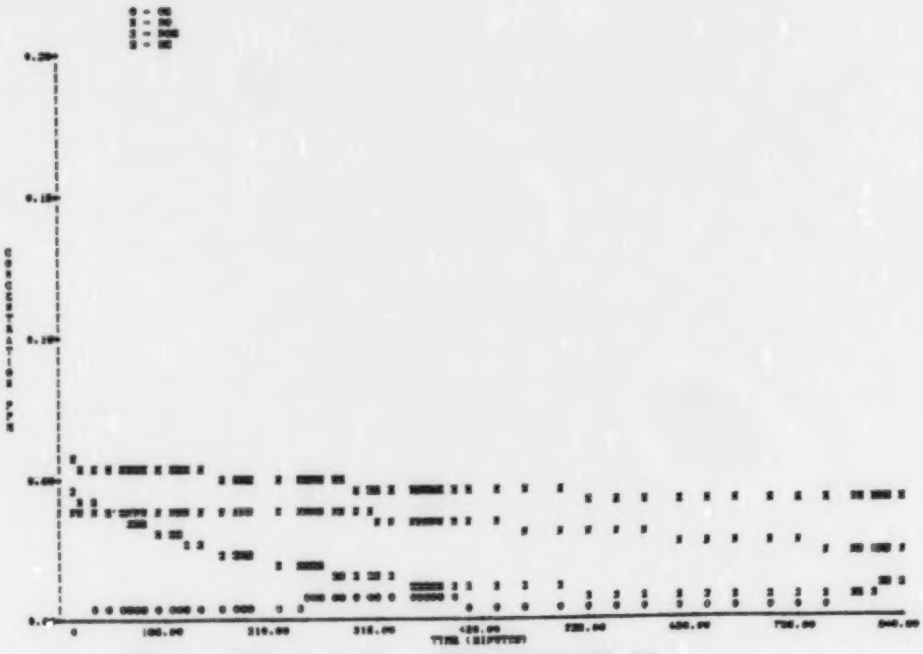
The original H-S mechanism contained six chemical species: NO, NO_2, O_3, CO, and two lumped hydrocarbon species representing reactive and unreactive hydrocarbons. Unreactive hydrocarbons did not enter the photochemical process at all; CO entered only marginally, by slightly enhancing the formation rate of ozone. However, the photochemistry primarily depended on the species NO, NO_2, O_3, and reactive hydrocarbons (RHC). Of these species, only NO_2 photolyzed to produce oxidizing radicals, the sine qua non of photochemical smog formation. The nitrogen oxides, NO and NO_2, also were assumed to be a minor source of radicals via the reactions $NO + NO_2 + H_2O \rightarrow 2HNO_2$ and $HNO_2 \rightarrow OH\cdot + NO$. Because HNO_2 was assumed to be present in steady-state concentrations, that species was eliminated from the computations and the net result was the reduction of NO_2 to NO and the production of OH radicals.

It is now known (Hecht et al., 1974a) that the photolysis of aldehydes is the major source of radicals during most of the photochemical process. The H-S chemistry neglects this reaction, with two major consequences. First is the major reduction in the reactivity of an atmospheric mix, with a consequential increase in the induction period--the time required to oxidize significant amounts of NO to NO_2. It is only after this induction period that ozone is efficiently produced, as illustrated in Figure A-1.

Second, radical production in the H-S mechanism proceeds according to the product of sunlight and NO_2 rather than the product of sunlight and aldehydes as more recent work has shown to be the case. Aldehyde



(a) Carbon-Bond Mechanism



(b) Hecht-Seinfeld Mechanism

FIGURE A-1. RESULTS OF TWO BOX MODEL SIMULATIONS (DIURNAL SUNLIGHT AND CONTINUOUS EMISSIONS TO REPRESENT URBAN TYPE CONDITIONS) FOR COMPARISON OF KINETIC MECHANISMS. The Hecht-Seinfeld mechanism used rate constants employed in the CDH study: note the negligible production of ozone.

concentrations are not proportional to NO_2 concentrations. The different production and destruction mechanisms of the two species assure that their peaks occur at different times. In order to provide for adequate radical and subsequent ozone production with the H-S mechanism, reaction rates or initial or inflow concentrations might be arbitrarily increased, but such artificial increases would not reconcile the H-S mechanism with the currently accepted principles (see Figure A-2).

In addition to new understanding of the chemical reactions involved in ozone production, a significant improvement has been introduced in the treatment of steady-state conditions at the modeling boundaries or at the beginning of the simulation.

Making the steady-state assumption for any species requires assuming that all transient effects have died out, and that the concentration of a species is equal to the production rate divided by the destruction rate. In the atmosphere, ozone is produced by the Reaction (A-29) and consumed by the Reaction (A-30):

$$NO_2 \xrightarrow{k_1} O_3 + NO \qquad \text{(A-29)}$$

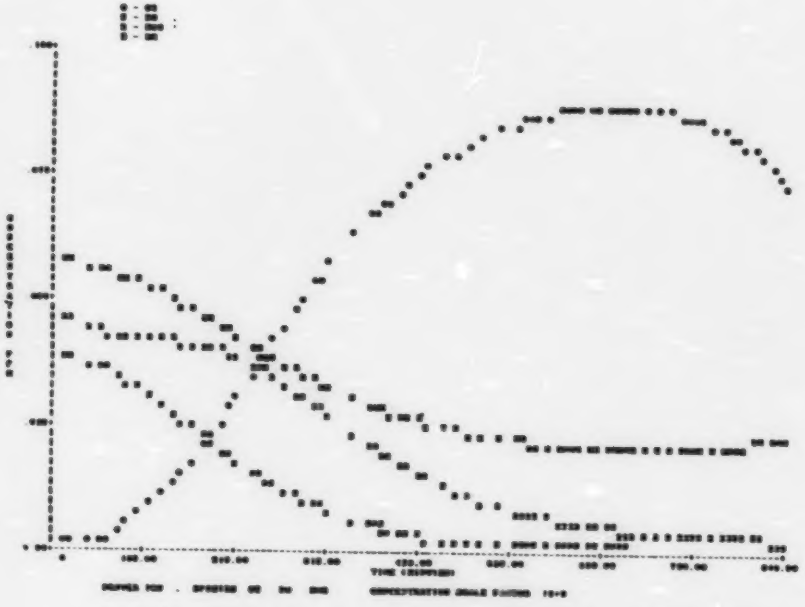
$$NO + O_3 \xrightarrow{k_3} NO_2 \qquad \text{(A-30)}$$

Thus the steady-state relationship for ozone is

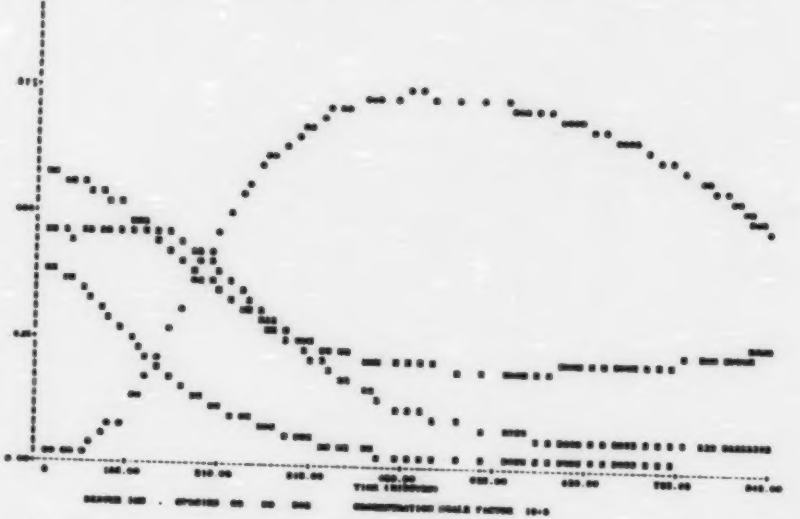
$$O_3 = \frac{k_1}{k_3} \frac{NO_2}{NO} \qquad \text{(A-31)}$$

where k_1 and k_3 are the rate constants in the reactions.

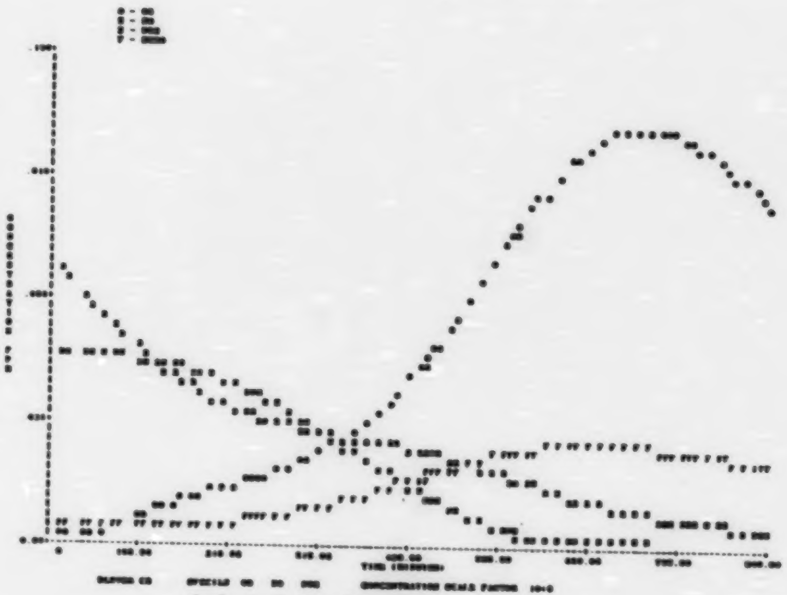
Invoking the steady-state assumption for the boundary conditions of the SAI APSP model is necessary because of the speed of these two reactions. Introducing material that is too far from steady state into the modeling region through the boundaries results in difficulties



(a) Increase in H-S Ozone-Hydrocarbon Reaction



(b) Increase in H-S Radical (Oxygen Atom)-Hydrocarbon Reaction



(c) C-B Mechanism

FIGURE A-2. RESULTS OF ATTEMPT TO "TUNE" H-S MECHANISM TO PRODUCE OZONE EQUIVALENT TO THE PREDICTIONS OF THE CARBON-BOND MECHANISM IN FIGURE A-1a. Note that in both H-S cases the ozone peak occurs much earlier than in the C-B case. The C-B ozone peaks were found to be in phase with observed peaks in validation experiments on the Denver Model.

for the finite difference method used in solving the chemical equations; at best it wastes computer time, at worst the model, unable to follow large fractional changes in small concentrations, will not function at all.

Using the steady-state assumption for ozone alone introduces a major flaw: in reality, all three species are varying. If, for example, one starts off with values of 0.01 ppm and 0.04 ppm for NO and NO_2 and 0.5/20 for k_1/k_3, Eq. (A-31) gives a value of 0.1 ppm for O_3. But a cursory glance at Eq. (A-29) immediately shows that O_3 cannot exceed NO_2. Obviously Eq. (A-31) is in error. In fact, the steady-state assumption must be invoked for all three species. This error in SAI's basic airshed model has been rectified only recently. Thus the 1969 Los Angeles validation studies were introducing as much as 0.15 ppm of ozone via the boundaries, as well as significant quantities of NO_x in the form of NO_2, already "primed" and ready to react with hydrocarbons, without the delay of the induction period.

The ozone concentrations computed in the APSP model runs made by the Colorado Department of Highways, using the H-S kinetics, were similarly enhanced by boundary condition values (a programming error accentuated this effect). Also, the CDH increased the sunlight factors somewhat above what could reasonably be expected in Denver, in order to get a better fit to observed data. Under the circumstances, this was perhaps the most reasonable thing for them to do.

In summation, then: the H-S kinetic mechanism contains flaws that make it unsuitable for modeling urban atmospheres. These flaws became obvious only with the advent of the second generation of models such as the 12-species Denver Model. The atmospheric testing of second-generation models is quite recent. Indeed, to a large extent, the present project is the first comparison of the two generations. But now that the comparison has been made, it is clear that the new chemistry, including aldehydes, must be used if we are to attempt to model the realities of urban atmospheres.

c. Choice of a Kinetic Mechanism for the Denver Model

SAI's initial airshed modeling efforts, started in 1972 under EPA Contract 68-02-0580, resulted in the development of the Hecht-Seinfeld-Dodge (H-S-D) kinetic mechanism (Hecht et al., 1974a). This work is described in three reports to the EPA: a detailed planning document (Seinfeld et al., 1973) and two final reports (Hecht et al., 1973, 1974b).

The H-S-D mechanism struck a balance between compactness of form and accuracy of prediction by treating the important inorganic smog reactions explicitly and by treating hydrocarbons in four groups, or "lumps": olefin, paraffin, aromatic, and aldehyde. It incorporated the latest knowledge of smog chemistry, but because of gaps in that knowledge it also incorporated some empirical parameters. The values of these parameters were chosen by fitting predicted concentration-time profiles to a set of smog chamber data.

The H-S-D mechanism was a significant improvement over the lumped mechanisms then available. The results presented by Hecht et al. (1974a) showed reasonable agreement with smog chamber data. In addition, by combining the numerical sensitivity and estimated uncertainty of each reaction and rate constant in the H-S-D mechanism, Hecht et al. (1974b) were able to determine which reactions and rate constants produced the greatest uncertainties in predictions and were thus most in need of further study. Some problems were encountered, however, in attempting to apply the mechanism to situations other than smog chamber experiments and to apply it outside the range of concentrations and hydrocarbon mixes upon which it was based (Demerjian et al., 1974).

These problems stemmed largely from the use of parameters that were based on smog chamber data, not on the fundamental chemistry. Incorrect fundamental chemistry and chamber-dependent phenomena could be compensated for or masked by these parameters. No single set of parameters would fit all smog systems, and there was little theoretical guidance for adjusting the parameters for systems for which no experimental data existed.

Meanwhile, technological progress in smog chamber construction and analytical capabilities was making it possible to obtain more detailed and more reliable data. At the same time, the application of advanced computer hardware and software was reducing both the time and cost of computer modeling. These developments made it possible, at least for simple smog chamber experiments (one, two, or three hydrocarbons present initially), to trace many of the major intermediate oxidation products of carbon and hydrogen atoms from the initial hydrocarbon to carbon dioxide and water. The combination of the need for a better mechanism and the availability of more reliable and detailed data led to a new phase in SAI's work--the development of explicit kinetic mechanisms.

Whereas a lumped mechanism treats hydrocarbons in groups or "lumps," an explicit mechanism attempts to account for the fundamental or elementary reactions of every atom. For example, the explicit mechanism for propylene and NO_x in a smog chamber contains over 60 reactions involving 35 species. Explicit mechanisms are based on studies of the chemical kinetics of individual reactions. The results of many of these studies have been compiled and evaluated [e.g., Hampson and Garvin (1975); Demerjian et al. (1974)]. When data for a particular elementary reaction are insufficient, its rate constant and products can often be estimated from analogous reactions using thermodynamic principles (Benson, 1975). Because explicit mechanisms are based on the fundamental chemistry, a poor fit between predictions and measurements for a given species can sometimes be traced to uncertainties in chemical reactions or inaccuracies in smog chamber experiments. For example, poor fits between predictions and measurements for some propylene/NO_x experiments in the evacuable smog chamber at the University of California at Riverside (UCR) led Durbin et al. (1975) to hypothesize that the intensity of light from the UV source in the chamber was decreasing more rapidly at short wavelengths than at long wavelengths. Subsequent measurements on replacement light sources at UCR were consistent with this hypothesis.

In the early stages of SAI's development of explicit mechanisms, smog chamber data could be fitted more closely with the parameterized H-S-D mechanism than with the explicit mechanisms. As knowledge of smog chemistry increased, this situation was reversed. At present, the explicit mechanisms predict smog chamber data better than the H-S-D mechenism, and without any adjustment of parameters they fit a much wider range of concentrations than does the H-S-D mechanism. They provide more detailed insight into the smog formation process. Because they are not as empirical, there is a theoretical justification for applying them outside the range of concentrations and hydrocarbon mixes used in smog chamber experiments.

One might question the usefulness of explicit mechanisms in a regional model. Since the mechanism for propylene and NO_x alone contains over 60 reactions, surely an explicit mechanism for urban smog would contain too many reactions to be of practical use. A condensed version of the explicit mechanisms would combine the advantages of a basis in elementary chemical reactions and speed of computation. Some months ago, SAI began development of a new condensed mechanism, the Carbon-Bond mechanism.

Like the H-S-D mechanism, the Carbon-Bond mechanism employs lumped chemical species, but there are important differences. The H-S-D mechanism treats groups of molecules (e.g., aldehydes), whereas the Carbon-Bond mechanism treats groups of similarly bonded carbon atoms (e.g., carbonyl carbons). The Carbon-Bond mechanism is far easier to use because it was designed to accept the types of data most commonly reported. But the most important difference is the scientific basis: whereas the H-S-D mechanism was of necessity somewhat empirical, the Carbon-Bond mechanism is derived from the fundamental chemical reactions in smog as representd by explicit mechanisms. Thus the Carbon-Bond mechanism is a condensation of our understanding rather than a parameterization of our uncertainty.

Although the Carbon-Bond mechanism was developed recently, it has been applied to some smog chamber experiments. Preliminary results (Whitten and Hogo, 1977) indicate that it is far more accurate than the H-S-D mechanism. Unquestionably, it is easier to apply, since it does not require the difficult task of estimating average carbon numbers and stoichiometric coefficients. Thus, the Carbon-Bond mechanism is the mechanism of choice in the analysis and simulation of Denver air quality. Information that follows indicates that its performance is excellent.

5. PARAMETERIZATION OF THE SAI DENVER MODEL

Tables A-4 and A-5 show the parameters used in the Denver Model. The form of the Carbon-Bond mechanism and the chemical reaction rates used are given in Table A-6. Of these parameters, the least sensitive are those for surface roughness and deposition velocities; the maximum variability that one would expect in these quantities would have little effect on predictions on the time scale of a day's simulation.

Similarly, while the NO_2 photolysis rate is an important model parameter, we are confident of our estimates of its magnitude (to within 10 percent). Thus we do not feel this to be a major source of model uncertainty.

To the extent that pollutants leave the modeling region and are then advected back into it later in the day, the assumed boundary conditions are in error, since the concentrations at the boundaries are held at background levels. However, this reentry only occurs in late afternoon, if it occurs at all, and so it has little effect on the predicted oxidant peak. Errors in the assumed background concentrations can be expected to have a less than 1 pphm effect on oxidant predictions.

The sensitivity of the model to changes in meteorological and total emissions factors is described elsewhere in this report.

TABLE A-4. NON-TIME-DEPENDENT PARAMETERS USED IN THE DENVER MODEL

Boundary Conditions

NO_x*	3 ppb	H_2O_2	0.01 ppb
O_3	2 pphm	HNO_2†	0.1 ppb max.

Olefins	0.4 ppb
Paraffins	35 ppbC
Aldehydes	1 ppb
Aromatics and ethylene	0.8 ppb
CO	0.1 ppm

Surface Roughness

0.5 meters over entire modeling region

Deposition Velocities

All set to zero

Emissions Splits by Weight

Olefins	0.031
Paraffins	0.65
Aldehydes	0.05
Aromatics	0.205

All else unreactive.

---

* NO and NO_2 vary with sunlight; O_3 remains essentially unchanged; NO/NO_x ratio varies from 0 to 0.6.

† HNO_2 varies according to steady-state relationship.

TABLE A-5. TIME-DEPENDENT PARAMETERS USED IN THE DENVER MODEL

(Midsummer)

Hour of Day	$k_1 (min^{-1})$*	Exposure Class†
0000	0	-1
0100	0	-1
0200	0	-1
0300	0	-1
0400	0	-1
0500	0	-1
0600	0.098	0
0700	0.22	1
0800	0.36	1
0900	0.456	2
1000	0.53	2
1100	0.576	3
1200	0.59	3
1300	0.58	3
1400	0.546	3
1500	0.47	2
1600	0.37	2
1700	0.25	1
1800	0.128	-1
1900	0	-1
2000	0	-1
2100	0	-1
2200	0	-1
2300	0	-1
2400	0	-1

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* See Table A-7 and Figure A-3 (k_1 increased by 10% for Denver altitude correction)

† -1 = night
0 = twilight
1→3 = low, medium, and strong sunlight.

TABLE A-6. THE CARBON-BOND MECHANISM USED IN THE DENVER MODEL

(a) Reactions

No.	Reaction	No.	Reaction	No.	Reaction
1	$NO_2 + h\nu \rightarrow NO + O$	14	$HO_2^{\cdot} + HO_2^{\cdot} \rightarrow H_2O_2 + O_2$	28	$CH_3O_2^{\cdot} + NO \rightarrow NO_2 + HCHO + HO_2$
2	$O + O_2\ (+M) \rightarrow O_3\ (+M)$	15	$PAN \rightarrow HC(O)O_2^{\cdot} + NO_2$	29	$HC(O)O_2^{\cdot} + NO \rightarrow NO_2 + CO_2 + HO_2^{\cdot}$
3	$O_3 + NO \rightarrow NO_2 + O_2$	16	$H_2O_2 + h\nu \rightarrow OH\cdot + OH\cdot$	30	$HC(O)O_2^{\cdot} + NO_2 \rightarrow PAN$
4	$O + NO_2 \rightarrow NO + O_2$	17	$OLE + OH\cdot \xrightarrow{O_2} HCHO + CH_3O_2^{\cdot}$	31	$CH_3O_2^{\cdot} + HO_2^{\cdot} \rightarrow CH_3OOH + O_2$
5	$O_3 + NO_2 \rightarrow NO_3 + O_2$	18	$OLE + O \xrightarrow{2O_2} HC(O)O_2^{\cdot} + CH_3O_2^{\cdot}$	32	$HC(O)O_2^{\cdot} + HO_2^{\cdot} \rightarrow HC(O)OOH + O_2$
6	$NO_3 + NO \rightarrow NO_2 + NO_2$	19	$OLE + O_3 \xrightarrow{O_2} HC(O)O_2^{\cdot} + HCHO + OH\cdot$		
7	$NO_3 + NO_2 + H_2O \rightarrow 2HNO_3$	20	$PAR + OH\cdot \xrightarrow{O_2} CH_3O_2^{\cdot} + H_2O$		
8	$HO_2^{\cdot} + NO_2 \rightarrow HNO_2$	21	$PAR + O \xrightarrow{O_2} CH_3O_2^{\cdot} + OH\cdot$		
9	$NO_2 + OH\cdot \rightarrow HNO_3$	22	$HCHO + OH\cdot \xrightarrow{O_2} HC(O)O_2^{\cdot} + H_2O$		
10	$HNO_2 + h\nu \rightarrow NO + OH\cdot$	23	$HCHO + h\nu \xrightarrow{2O_2} \alpha HC(O)O_2^{\cdot} + \alpha HO_2^{\cdot}$		
11	$NO + OH\cdot \rightarrow HNO_2$	24	$ARO + OH\cdot \xrightarrow{O_2} HCHO + CH_3O_2^{\cdot}$		
12	$CO + OH\cdot \xrightarrow{O_2} CO_2 + HO_2^{\cdot}$	25	$ARO + O \xrightarrow{2O_2} HC(O)O_2^{\cdot} + CH_3O_2^{\cdot}$		
13	$HO_2^{\cdot} + NO \rightarrow OH\cdot + NO_2$	26	$ARO + O_3 \xrightarrow{O_2} HC(O)O_2^{\cdot} + HCHO + OH\cdot$		
		27	$ARO + NO_3 \rightarrow Products$		

TABLE A-6 (Concluded)

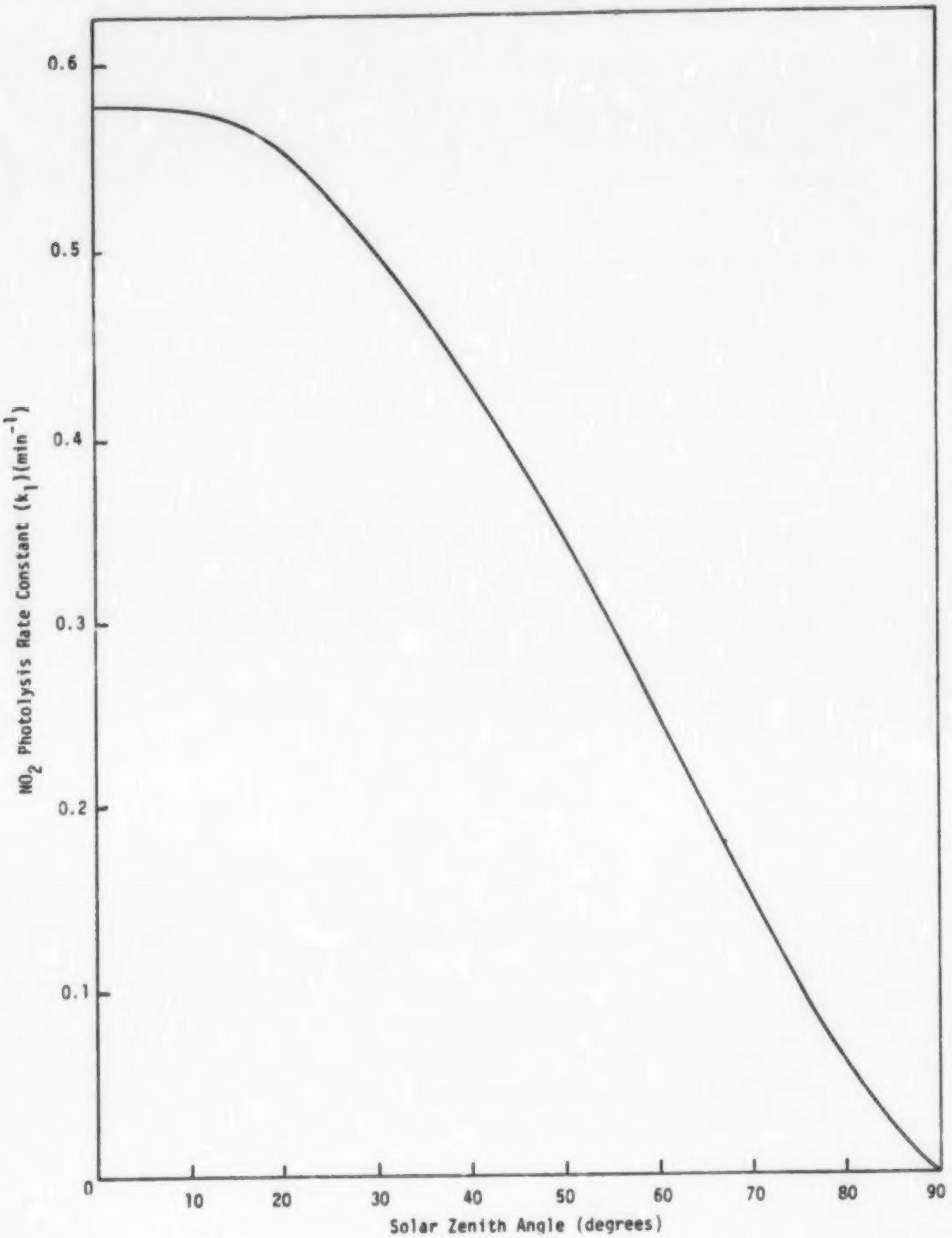
(b) Rate Constants*

Reaction Number	Rate Constant	Reaction Number	Rate Constant	Reaction Number	Rate Constant
1	k_1[†]	14	4.0×10^3	28	2.0×10^3
2	2.08×10^{-5}	15	2.0×10^{-2}	29	2.0×10^3
3	2.52×10^1	16	$7.0 \times 10^{-4} k_1$	30	1.5×10^2
4	1.34×10^4	17	3.8×10^4	31	4.0×10^3
5	5×10^{-2}	18	5.3×10^3	32	4.0×10^3
6	1.3×10^4	19	1.5×10^{-2}		
7	2.0×10^{-3}	20	1.3×10^3		
8	3.0×10^1	21	2.0×10^1		
9	9.0×10^3	22	2.0×10^4		
10	$1.9 \times 10^{-1} k_1$	23	$6.0 \times 10^{-3} k_1$		
11	9.0×10^3	24	8.0×10^3		
12	2.06×10^2	25	3.7×10^1		
13	2.0×10^3	26	2.0×10^{-3}		
		27	5.0×10^1		

---

[*] In units of $ppm^{-1}min^{-1}$ except for photolysis reactions and Reaction 15 (units of min^{-1}) and Reaction 7 (units of $ppm^{-2}min^{-1}$).

[†] The rate constant for NO_2 photolysis, k_1, depends on the UV intensity. In the Denver Model k_1 was determined by using the solar zenith angles in Table A-7 and the values of k_1 in Figure A-3.



Source; Killus et al. (1977)

FIGURE A-3. ESTIMATED GROUND-LEVEL NO_2 PHOTOLYSIS RATE CONSTANT AS A FUNCTION OF SOLAR ZENITH ANGLE

TABLE A-7. SOLAR ZENITH ANGLES FOR DENVER

(39.75° latitude, 105° longitude)

29 July		15 November	
Hour	Angle	Hour	Angle
500.00	110.14	500.00	90.08
530.00	104.46	530.00	84.76
600.00	98.88	600.00	79.28
630.00	93.43	630.00	73.68
700.00	88.15	700.00	67.98
730.00	83.09	730.00	62.24
800.00	78.29	800.00	56.48
830.00	73.82	830.00	50.74
900.00	69.75	900.00	45.08
930.00	66.16	930.00	39.57
1000.00	63.14	1000.00	34.32
1030.00	60.77	1030.00	29.50
1100.00	59.14	1100.00	25.38
1130.00	58.30	1130.00	22.38
1200.00	59.14	1200.00	21.01
1230.00	60.77	1230.00	21.57
1300.00	63.14	1300.00	23.93
1330.00	66.17	1330.00	27.63
1400.00	69.76	1400.00	32.20
1430.00	73.83	1430.00	37.29
1500.00	78.29	1500.00	42.71
1530.00	83.09	1530.00	48.32
1600.00	88.16	1600.00	54.04
1630.00	93.44	1630.00	59.80
1700.00	98.89	1700.00	65.56
1730.00	104.48	1730.00	71.29
1800.00	110.16		
1830.00	115.90		
1900.00	121.66		
1930.00	127.42		
2000.00	133.11		

We are thus left with those factors pertaining to photochemical reactivity: splits of hydrocarbon emissions among classes and chemical rate constants. Ideally, these parameters would be directly available from data or theoretical considerations. Some of the chemical rate constants are in fact obtained this way. However, many of these factors including several of critical importance, are, of necessity, estimated. Thus, any simulation exercise that agrees well with observations in its initial trials must be regarded as containing significant amounts of luck. This is very nearly what happened in this study.

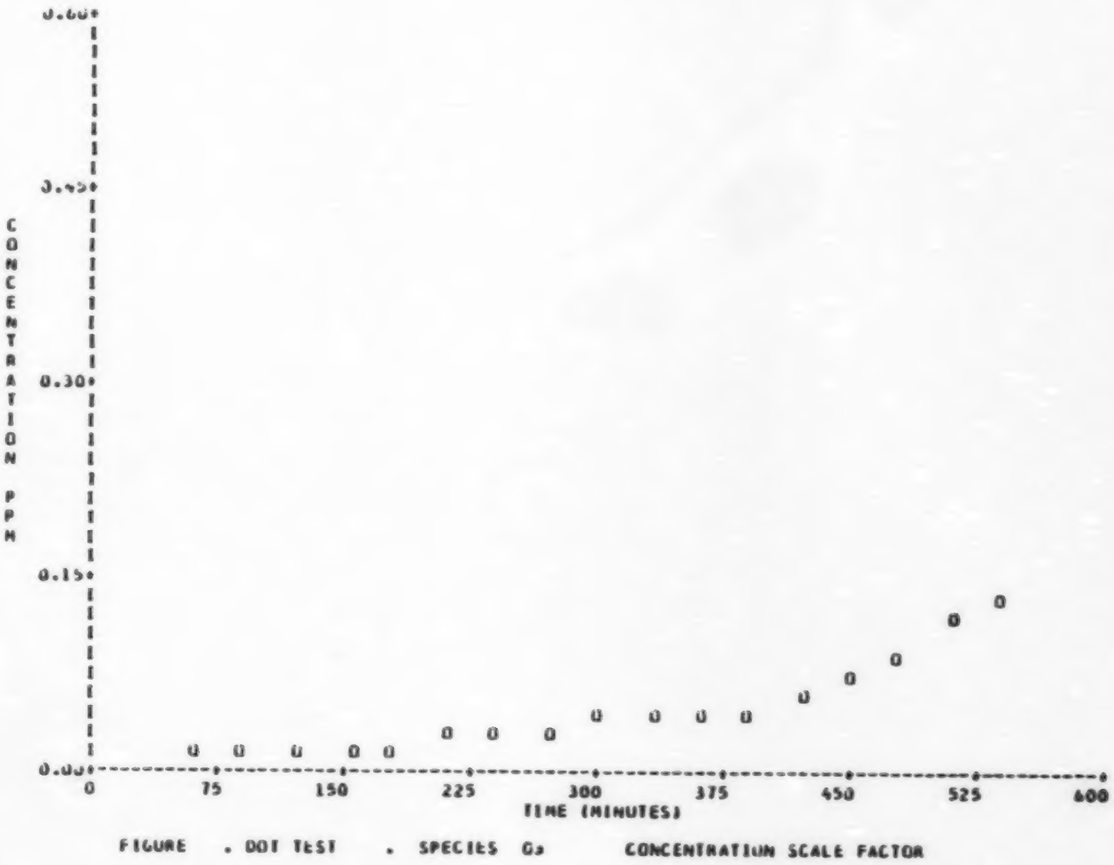
Figures A-4, A-5, and A-6 represent results of a trajectory analysis of three air parcels which passed over Department of Health air quality stations 2, 3, and 4 at 12 noon, and 10 and 8 a.m. respectively on 29 July 1975 (see Table A-8). The two sets of simulations represent aldehyde photolysis rates of 0.005 x k_1 and 0.006 x k_1.

TABLE A-8. OBSERVATIONS AT COLORADO DEPT. OF HEALTH MONITORING STATIONS AND TRAJECTORY MODEL PREDICTIONS FOR OZONE

	Station 2	Station 3	Station 4
Observations	8 pphm	10 pphm	11 pphm
Predictions 1	4 pphm	10 pphm	8 pphm
2	4.5 pphm	12 pphm	9 pphm

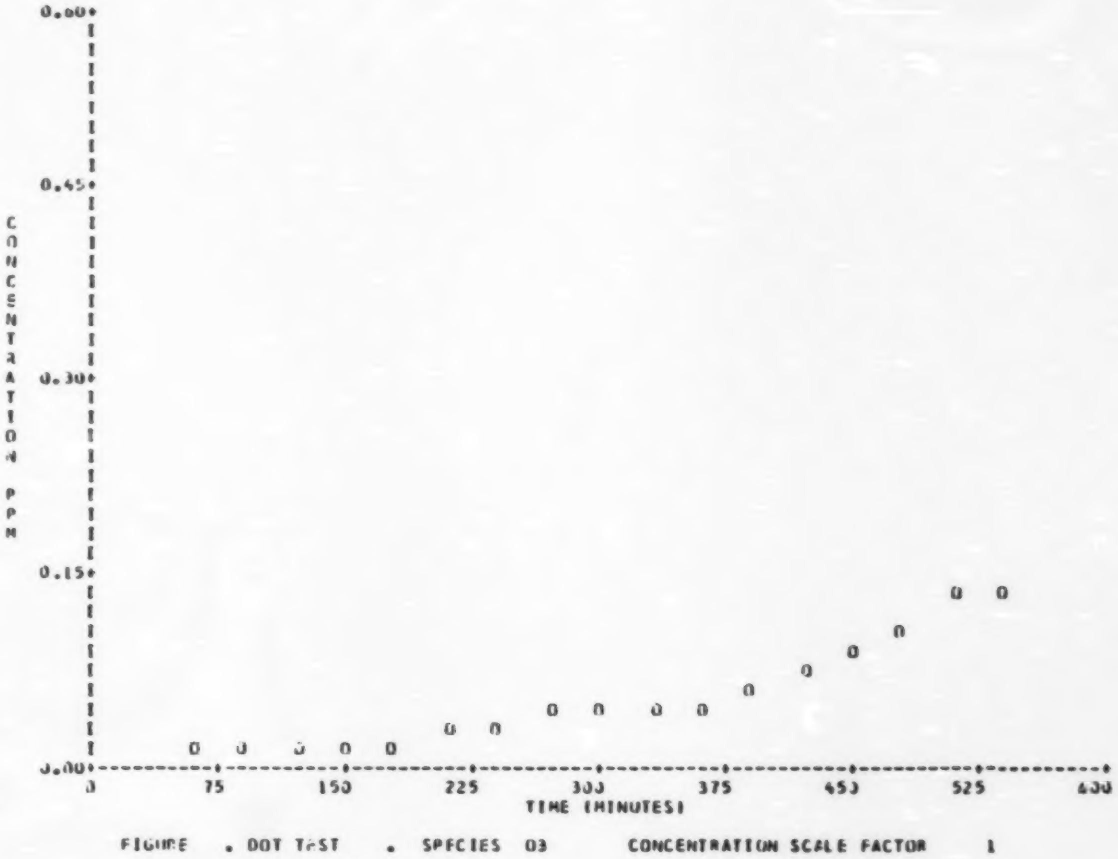
The aldehyde photolysis rate is the main adjustable reactivity parameter because it is only known to within about 50 percent accuracy and because it varies naturally on the order of 20 percent.

On the basis of these six simulations we chose the aldehyde photolysis rate to be 0.006 x k_1. This is the only parameter adjustment made in the kinetic mechanism in this project. The exceptionally good agreement between station observations and predictions must be viewed as a combination of good science and luck.



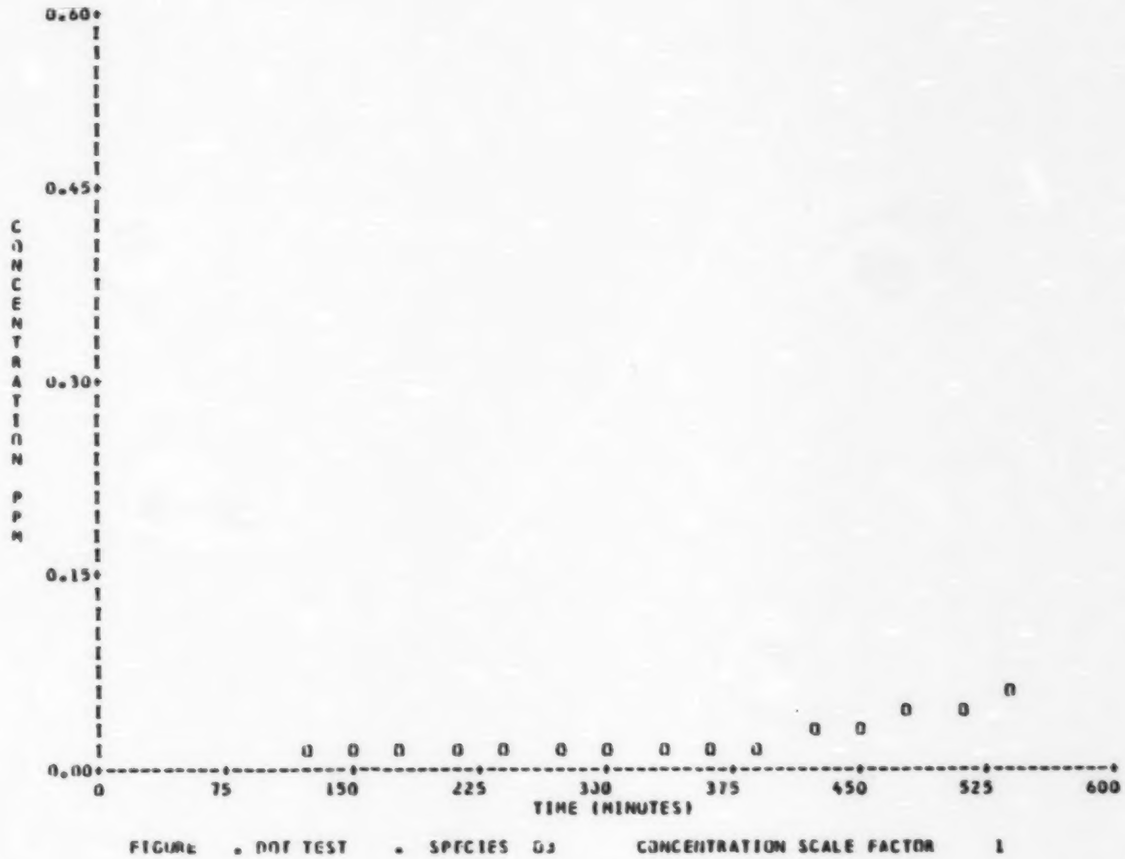
(a) 0.005 Aldehyde Factor

FIGURE A-4. TRAJECTORY ANALYSIS FOR HEALTH STATION 2



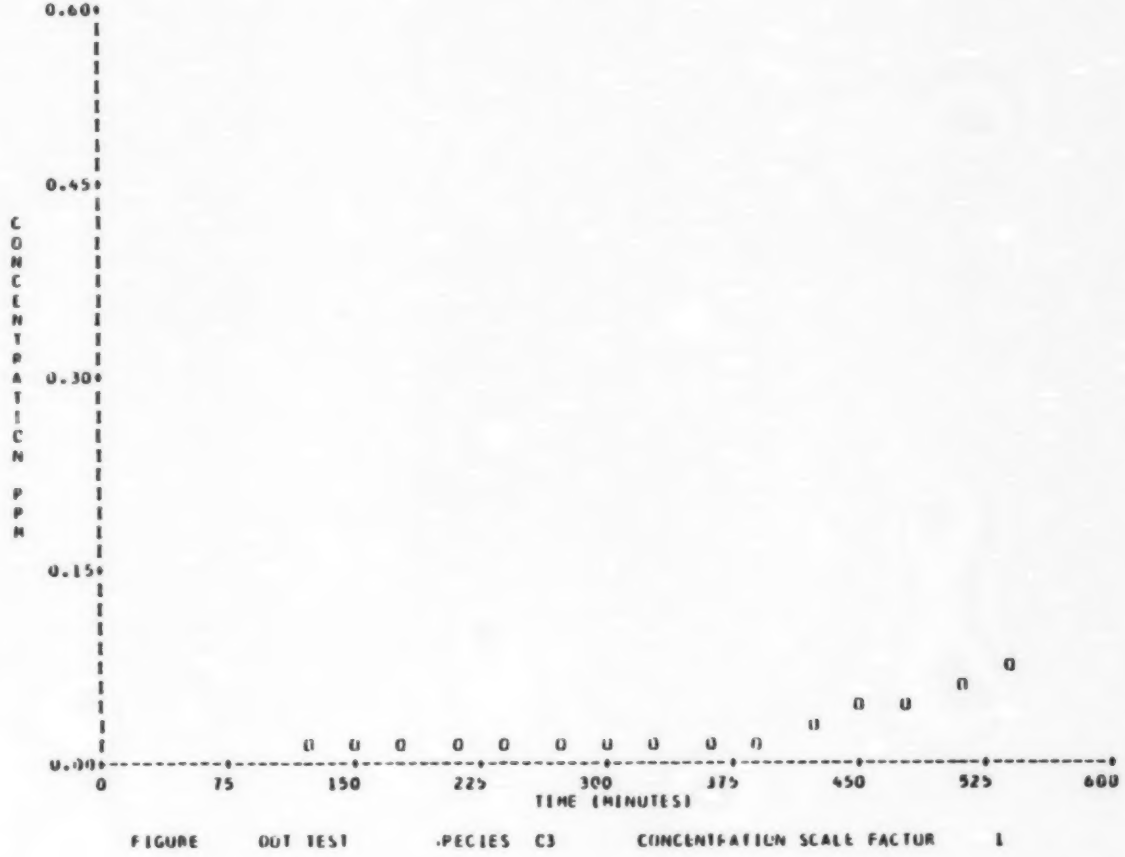
(b) 0.006 Aldehyde Factor

FIGURE A-4 (Concluded)



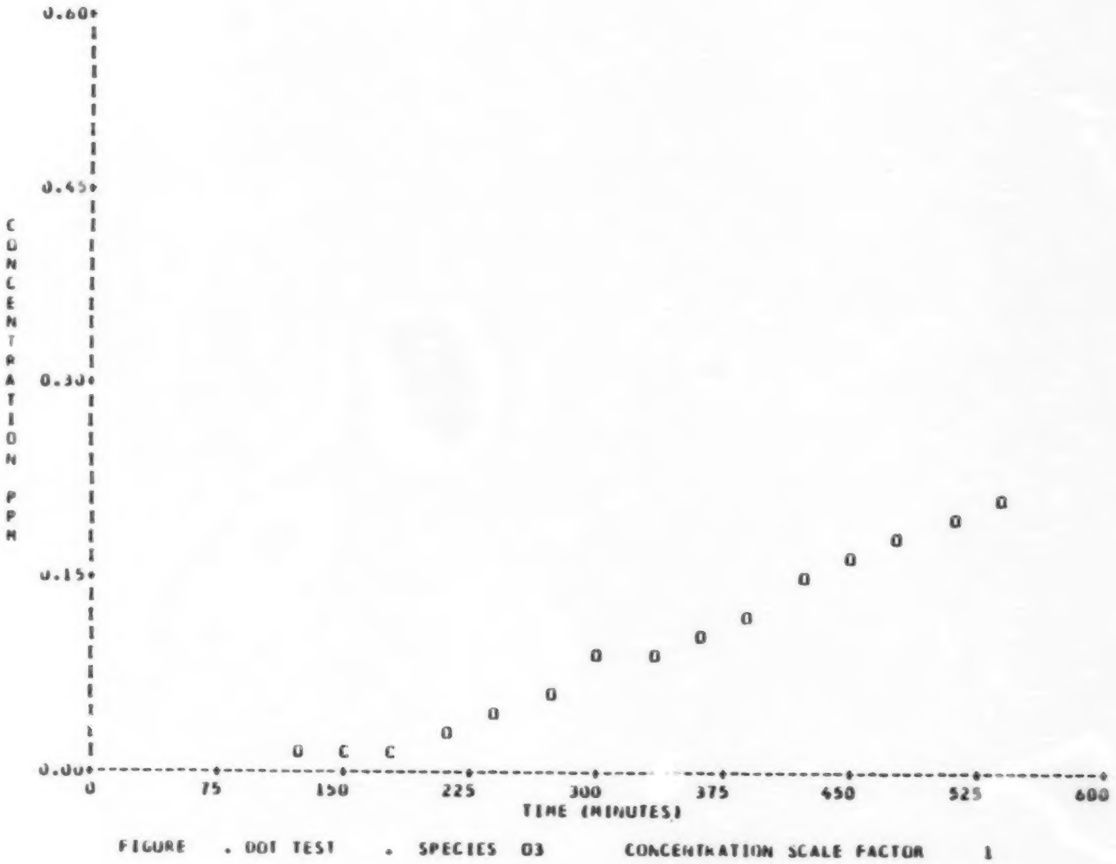
(a) 0.005 Aldehyde Factor

FIGURE A-5. TRAJECTORY ANALYSIS FOR HEALTH STATION 3



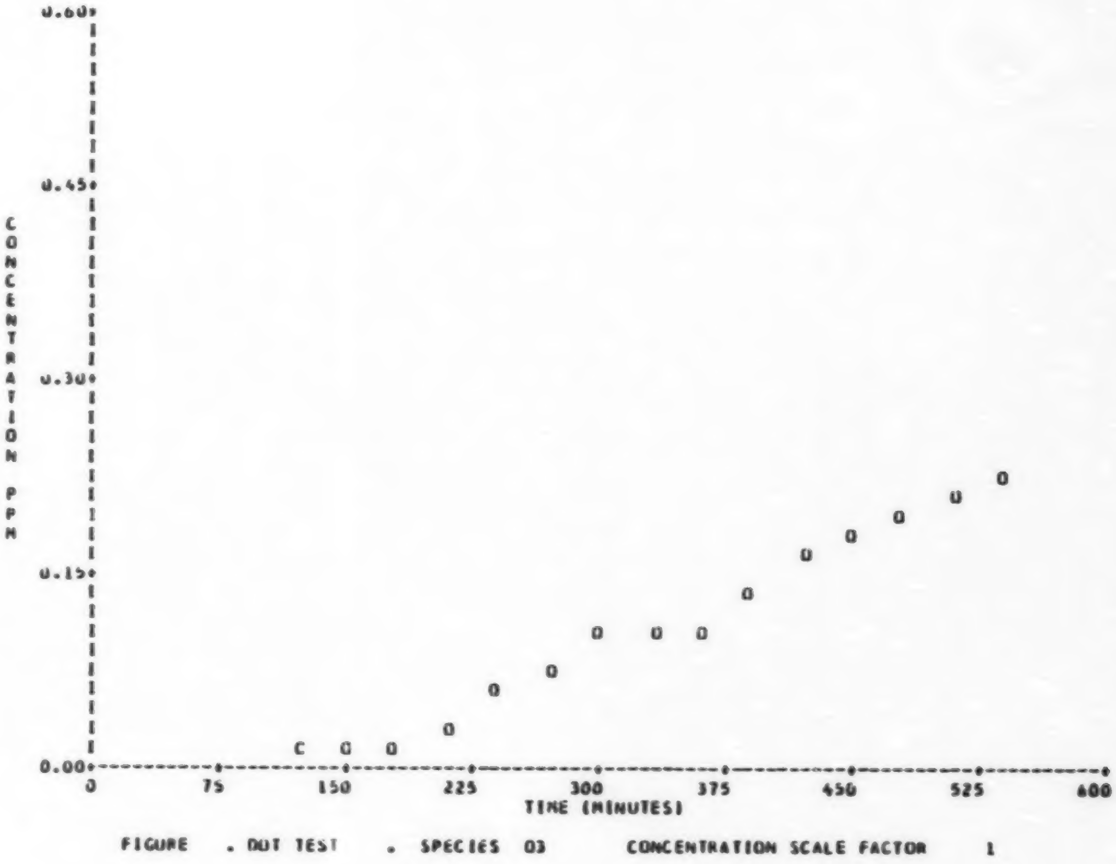
(b) 0.006 Aldehyde Factor

FIGURE A-5 (Concluded)



(a) 0.005 Aldehyde Factor

FIGURE A-6. TRAJECTORY ANALYSIS FOR HEALTH STATION 4



(b) 0.006 Aldehyde Factor

FIGURE A-6 (Concluded)

6. THE CLIMATOLOGICAL DISPERSION MODEL (CDM)

The CDM is used for calculating long term, e.g., seasonal or annual, average concentrations for quasi-stable pollutant species. Input to the model includes a detailed specification of the magnitude and distribution of pollutant emissions from point and area sources, together with the frequency of occurrence of various meteorological conditions for the time span under consideration.

The basis for computing the dispersion of pollutants in CDM is that the steady-state distribution of concentrations for a homogeneous atmosphere from a continuously emitting source is given by a Gaussian plume formula. The pollutant concentrations at each receptor are calculated by adding contributions of pollutants from each upwind source (within a $\frac{2\pi}{16}$ radian sector). This summation is taken over each combination of wind speed, direction, and atmospheric stability class, weighted by the estimated probability of occurrence of that combination. These probability functions are derived from historical meteorological records.

The major strong points of the CDM are:

> It is relatively inexpensive to run.
> It includes a good description of the emissions inventory. Major point sources and their characteristics can be identified and included, while dispersed sources can also be accounted for.
> It includes a basic description of the climatology of the modeling region--enough to characterize average meteorology for the time span being considered. Since CDM considers the distribution of wind speeds and directions over a period, on the average it does reproduce correctly the dilution of emissions due to wind. It also takes average mixing heights into consideration.

- The CDM allows data on pollutants that are subject to annual air quality standards to be assessed. Models that calculate one-hour-average concentrations of pollutants for a single study day cannot easily be used to predict annual averages.

The major assumptions included in the CDM are:

(1) As pollutants are carried downwind from their sources, they spread horizontally across sectors ($\frac{2\pi}{16}$ radians) and disperse vertically according to a Gaussian plume formula. This formula is modified to account for the existence of a mixing layer with finite depth. For receptors at large distances downwind from the source a uniform vertical distribution of concentrations is assumed. For short distances the Gaussian formula is used, and for intermediate distances an interpolation formula is provided.

(2) Meteorological conditions can be described by a distribution function of wind speed, direction, and atmospheric stability class. This function is usually derived from records kept at a local airport and is assumed to be invariant over the modeling region. Allowance is made for vertical variation of wind velocity by a power law relationship that is a function of stability class.

(3) The effective height of area sources is constant over the modeling region. All sources that cannot be identified individually as point sources are gridded into area sources.

(4) Source strengths do not vary with time, or if they do, such variation is not correlated with meteorological variables. This assumption conforms to the characteristics of most emissions inventories, in which long-term temporal variations of source strengths are unaccounted for. However, in reality, such temporal variations are common. For example, there are daily and seasonal patterns in power demand, which in turn affect power station emissions. Use of the formulas in the CDM, with its steady-state assumption, requires that emissions

are evenly spread among the possible combinations of meteorological conditions.

(5) No material is lost from the plume to the ground and there is no gravitational settling within the plume.

(6) The diffusion coefficents and depth of the mixing layer may be parameterized in terms of atomspheric stability classes.

(7) Pollutants are carried in straight lines at constant speed from source to receptor. This treatment does not account for air parcel trajectories changing direction when the wind shifts, nor for spatial variations due to topography or local heating.

(8) Only sources within the modeling region contribute to observed pollution levels. This means that pollutants blown into the region from outside sources are not accounted for.

Before interpreting the results from the CDM, it should be noted that the NO_2 concentrations obtained from the CDM are calculated considering all NO_x emissions as being NO_2, even though at their sources they are predominantly NO. This treatment correctly accounts for the eventual conversion of NO to NO_2 in the atmosphere. Because the conversion is not complete except in the presence of sufficient ozone (which is not available during the early morning, when a large amount of the daily NO_x is emitted), the pollutant plumes will have a high NO/NO_2 ratio for long travel distance during morning commuter rush hours. Therefore the use of NO_x as a surrogate for NO_2 will result in serious overpredictions of NO_2 concentrations, particularly near the sources. Farther downwind, where the plumes are more diffuse, the NO_x will be mostly NO_2. Thus, for a given receptor, without calibration the CDM will overpredict NO_2 concentrations in plumes from nearby sources and predict more correctly for sources at some larger distance. The result will be a net overprediction of NO_2 concentrations over the entire modeling region but the peak concentrations, being most influenced by nearby sources, will exhibit the greatest overprediction.

The particulate concentrations predicted by the CDM are based, as was pointed out above, on the assumption that there is no gravitational settling in the plume or loss of material from the plume to the ground. This assumption seems inconsistent with the expected large particle size of some types of emissions, for example, those from street sanding.

A further potential problem in interpreting the results from the CDM arises because it is a calibrated model. By this we mean that a linear transformation is made to the calculated concentrations to obtain the predicted ones. The experimental data used to obtain the transformation are taken from monitors that are often placed at points where large concentrations of pollutants are expected, such as beside a highway. Since the concentrations at these points are much higher than the average concentrations over the area representative of the spatial resolution of the model (on the order of a square mile), an upward bias is imparted to all of the predicted concentrations reported.

Calibration cannot remove difficulties in interpreting NO emissions as NO_2. NO_x air quality data are available for CDM calibration only at the downtown CAMP station. Thus calibration might approximately correct the CDM overprediction at this site, but would then apply this scaled reduction at remote sites where substantial conversion has occurred. Most importantly, the calibration derived for one year cannot be valid for subsequent years if the mix of photochemical precursors change. Earlier in this report, Denver Model results are described that show decreases of NO_2 when NO emissions are increased.

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APPENDIX B
EMISSIONS ANALYSIS

APPENDIX B
EMISSIONS ANALYSIS
by Pravin V. Mundkur

For the purpose of evaluating and modeling the present and future air quality in the Denver metropolitan region, SAI obtained a number of emissions files of estimated present and future emissions of various air pollutants including carbon monoxide, particulates, oxides of nitrogen, and hydrocarbons. These emissions data were compiled primarily by the staff of the Air Pollution Control Division of the Colorado Department of Health and by the Colorado Division of Highways. Various other groups interacted with the above two state departments in this estimation process; they include the Environmental Protection Agency (EPA), the Denver Regional Council of Governments (DRCOG), and the Regional Transportation District (RTD).

SAI used the emissions data files primarily as inputs for the Denver Model and the Climatological Dispersion Model (CDM). However, substantial information can be gained from these files without the use of any models. SAI wrote separate computer programs to bring out the following information:

- Year-to-year variations in overall pollutant loading levels.
- Year-to-year variations in pollutant loading from subregions of the entire region selected for the modeling effort. The subregions are the same as those chosen for the sensitivity study.
- Relative contributions of various source categories to the overall pollutant loading.

Such an analysis of these emissions files provides a preliminary, although crude, assessment of the trends in air quality that is free from the limitations of the models used. Further, the study of the emissions from the various subregions is useful in assessing their relative impacts on air quality (as in the sensitivity study). Finally, the identification of the relative contributions of various source categories to the overall pollutant burden should be of great help in planning the most effective mitigation strategies. For these reasons, this appendix has been prepared to describe the results of SAI's in-depth analysis of the air pollutant emissions in the Denver metropolitan region.

This presentation is organized into a number of sections. In the first we summarize the present and potential emissions problem in the Denver metropolitan region. In Section 2 we take a brief look at federal and state emissions regulations as they apply to the emissions from highway and other traffic in this region. Section 3 presents an overview of the methodology used to arrive at the emissions estimates. Section 4 presents an analysis of the emissions files used as inputs to CDM and Section 5 presents an analysis of the files input to the Denver Model.

1. OVERVIEW OF PRESENT EMISSIONS IN THE DENVER REGION

The air pollutants that constitute the main problem in the Denver metropolitan region at present are carbon monoxide, particulates, reactive and unreactive hydrocarbons, and nitrogen oxides. Traffic, both highway and nonhighway, accounts for a major fraction of the emissions of pollutants: roughly 80 percent of the hydrocarbons, 30 to 40 percent of the nitrogen oxides, and about 90 percent of the carbon monoxide. While automobiles and other vehicles do not directly contribute a high proportion of the particulate emissions in the Denver metropolitan region, street sanding operations, which are related to the operation of these vehicles, contribute from 45 to 60 percent of the total particulate emissions.

Next to automobiles and other traffic, point sources are the most significant contributors to total emissions. Emissions from large point sources account for as much as 50 percent of the total emissions of nitrogen oxides.

As may be expected, a high proportion of the total emissions of any pollutant occurs in the Central Denver (Metro) subregion. The emissions flux is from 30 to 100 percent higher here than in any other subregion. A suprisingly high proportion (more than 50 percent) of the nitrogen oxides emissions lies outside any of the seven subregions delineated for the sensitivity study. An apparent reason for this is that more than 90 percent of the emissions from large point sources lie outside these subregions and large point sources account for a major portion (about 50 percent) of the emissions of nitrogen oxides.

By the year 2000, the emissions of particulates are projected to rise to roughly 180 percent of their 1974 level and the nitrogen oxides emissions to about 150 percent of that level, if events proceed in accordance with the JRPP plan. In contrast, both carbon monoxide and hydrocarbon emissions are expected to fall to roughly 55 percent of their 1974 levels by the year 2000. Over this same period, the emissions appear to rise most rapidly in the Jeffco-Urban and South Metro subregions, where the most rapid development is projected to take place.

2. EMISSIONS STANDARDS AND REGULATIONS APPLICABLE TO HIGHWAY AND OTHER TRAFFIC

The Federal Motor Vehicles Control Program, which is being implemented as a consequence of the Clean Air Act of 1970, requires a phased reduction in automotive emissions of hydrocarbons, carbon monoxide, and oxides of nitrogen to specified fractions of the 1971 emission levels. The original deadlines for achieving the ultimate lowered emission rates were 1975 for hydrocarbons and carbon monoxide and 1976 for oxides of nitrogen. Difficulties associated with meeting these deadlines have resulted in two one-year postponements by the Administrator of the Environmental Protection Agency and a one-year delay from Congressional action. Thus the present deadline for meeting the original statutory standards is 1978. Table B-1 summarizes the allowable emissions rates from automobiles manufactured in different years according to the current Federal Motor Vehicle Control Program. Figure B-1 is a graphical presentation of these Federal standards for cars and light-duty trucks.

The emissions factors used in this study were based on the 1978 deadline for the Federal Motor Vehicles Control Program. Pending amendments to the Clean Air Act could affect the estimates of emission factors and hence could alter the results of this study. For instance, further delays in the deadline by a year or two would probably result in higher emissions in 1980 and 1985 than estimated here, but emissions in 1990 and 2000 would be largely unaffected since emissions are expected to be stabilized by then. Any amendments that permanently alter the statutory emissions standards would certainly affect the emissions estimates for future years.

One of the pending Clean Air amendments would relax the original nitrogen oxides standard of 0.4 grams per mile to 1.0 grams per mile. It is possible to estimate roughly the impact of such a relaxation on total nitrogen oxides emissions in the year 2000. In that year the estimated NO_x emissions are roughly 270 tons per day (as NO_2). Of these emissions about 120 tons per day (as NO_2) are due to automobiles. If the auto emissions in the year 2000 are stabilized and the emissions standard is relaxed from 0.4 to 1.0 grams per mile, the auto emissions may be expected to be larger by a factor of 1.0/0.4, or 300 tons per day rather than 120. Including the estimated 150 tons of NO_x per day from nonauto sources in the year 2000, the total estimated emissions are 450 tons per day, which is an increase of 67 percent.

3. METHODOLOGIES USED FOR ESTIMATION AND PROJECTION OF EMISSIONS

A comprehensive discussion of the methodology used by the Colorado Department of Health is contained in the Denver AQMA report for the years 1974, 1980, and 1985. A discussion of the methodology used by

TABLE B-1. FEDERAL AND CALIFORNIA NEW VEHICLE EMISSIONS STANDARDS

(a) Passenger Cars and Light-Duty Trucks

YEAR	STANDARD	COLD START TEST	HYDROCARBONS	CARBON MONOXIDE	OXIDES OF NITROGEN
Prior to controls		7-mode	850 ppm	3.4%	1000 ppm
		7-mode	(11 gm/mi)	(80 gm/mi)	(4 gm/mi)
1966-1967	Calif.	7-mode	275 ppm	1.5%	no std.
1968-1969	Calif. &	7-mode			
	Federal	50-100 CID	410 ppm	2.3%	no std.
		101-140 CID	350 ppm	2.0%	no std.
		over-140 CID	275 ppm	1.5%	no std.
1970	Calif. & Federal	7-mode	2.2 gm/mi	23 gm/mi	no std.
1971	Calif.	7-mode	2.2 gm/mi	23 gm/mi	4 gm/mi
	Federal	7-mode	2.2 gm/mi	23 gm/mi	-
1972	Calif.	7-mode or	1.5 gm/mi	23 gm/mi	3 gm/mi
		CVS-1	3.2 gm/mi	39 gm/mi	*3.2 gm/mi
	Federal	CVS-1	3.4 gm/mi	39 gm/mi	-
1973	Calif.	CVS-1	3.2 gm/mi	39 gm/mi	3 gm/mi
	Federal	CVS-1	3.4 gm/mi	39 gm/mi	3 gm/mi
1974	Calif.	CVS-1	3.2 gm/mi	39 gm/mi	2 gm/mi
	Federal	CVS-1	3.4 gm/mi	39 gm/mi	3 gm/mi
1975 **PC	Calif.	CVS-2	0.9 gm/mi	9 gm/mi	2.0 gm/mi
**PC	Federal	CVS-2	1.5 gm/mi	15 gm/mi	3.1 gm/mi
**LDT	Calif.	CVS-2	2.0 gm/mi	20 gm/mi	2.0 gm/mi
**LDT	Federal	CVS-2	2.0 gm/mi	20 gm/mi	3.1 gm/mi
1976 **PC	Calif.	CVS-2	0.9 gm/mi	9 gm/mi	2.0 gm/mi
**PC	Federal	CVS-2	1.5 gm/mi	15 gm/mi	3.1 gm/mi
**LDT	Calif.	CVS-2	0.9 gm/mi	17 gm/mi	2.0 gm/mi
**LDT	Federal	CVS-2	2.0 gm/mi	20 gm/mi	3.1 gm/mi
1977† **PC and LDT	Calif	CVS-2	0.41 gm/mi	9 gm/mi	1.5 gm/mi
	Federal	CVS-2	1.5 gm/mi	15 gm/mi	2.0 gm/mi
1978 **PC and LDT	Federal	CVS-2	0.41 gm/mi	3.4 gm/mi	0.4 gm/mi

* 7-Mode Hot Start

**PC-Passenger Cars LDT-Light Duty Trucks

† The 1977 NOx standards have not been officially adopted at this time

TABLE B-1. (Concluded)

(b) Heavy-Duty Vehicles (Over 6,000 Pounds)

YEAR	STANDARD	HYDRO-CARBONS	CARBON MONOXIDE	OXIDES OF NITROGEN
*1969-1971	State-gasoline	275 ppm	1.5%	no std.
1972	State-gasoline	180 ppm	1.0%	no std.
1973-1974	State-gasoline & diesel	HC + NOx = 16 gm/BHP hr. CO = 40 gm/BHP hr.		
1975-1976	State-gasoline & diesel	HC + NOx = 10 gm/BHP hr. CO = 30 gm/BHP hr.		
1977	State-gasoline & diesel	HC + NOx = 5 gm/BHP hr. CO = 25 gm/BHP hr.		

gm/BHP hr. grams per brake horsepower-hour

* Federal standards remained at this level through 1973. The Federal Government adopted standards for heavy-duty gasoline and diesel vehicles for 1974 and subsequent model years which are identical to California's 1973-74 standards.

State Smoke Standards for Heavy-Duty Vehicles

1971 and later vehicles may discharge smoke no darker than Ringelman 1 or 20 percent opacity for up to 10 seconds.

Vehicles sold before 1971 may discharge smoke no darker than Ringelman 2 or 10 percent opacity for up to 10 seconds.

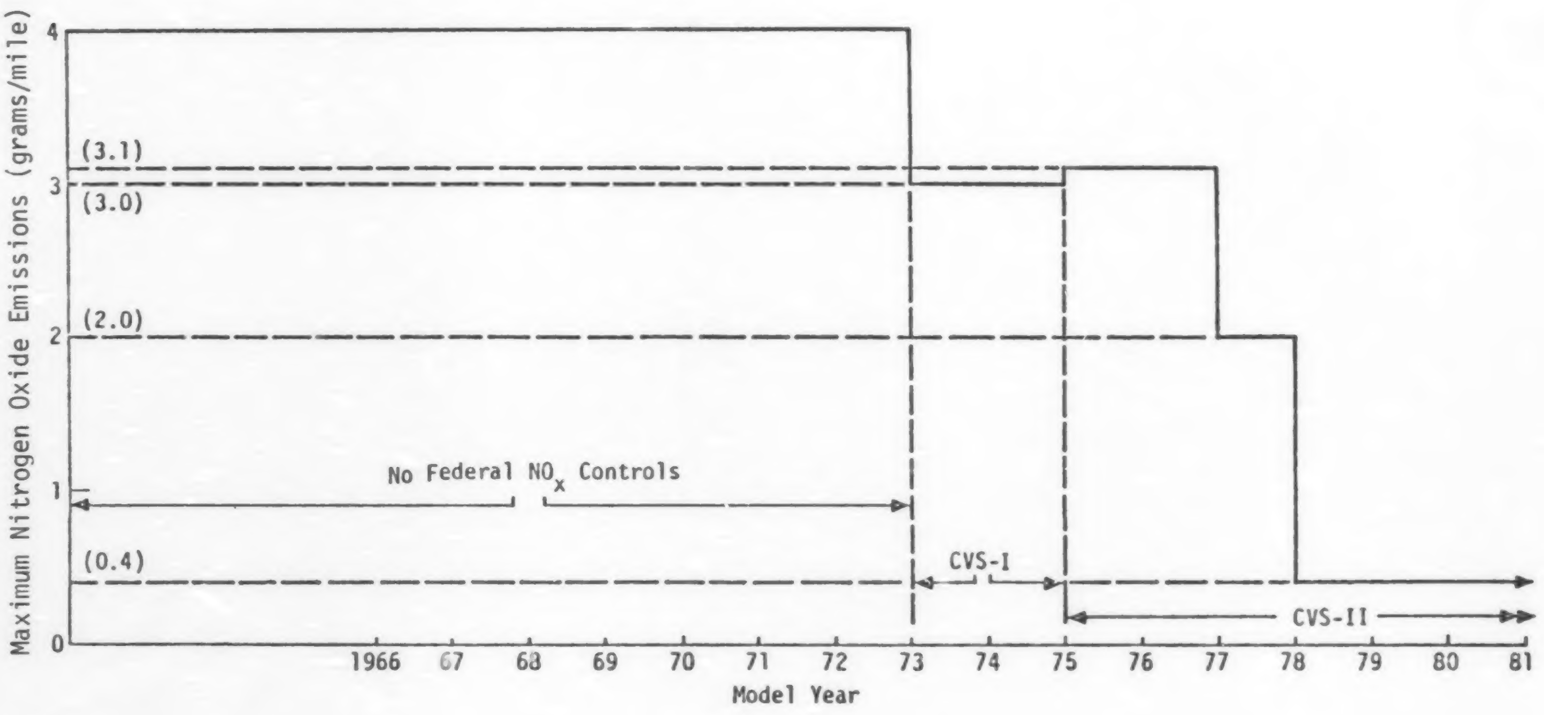
Crankcase Emissions

On all new vehicles manufactured for sale in California after January 1, 1964, crankcase emissions are virtually zero. Comparable Federal standards became effective in 1968 for light-duty vehicles, and 1970 for heavy-duty vehicles.

Evaporative Emissions

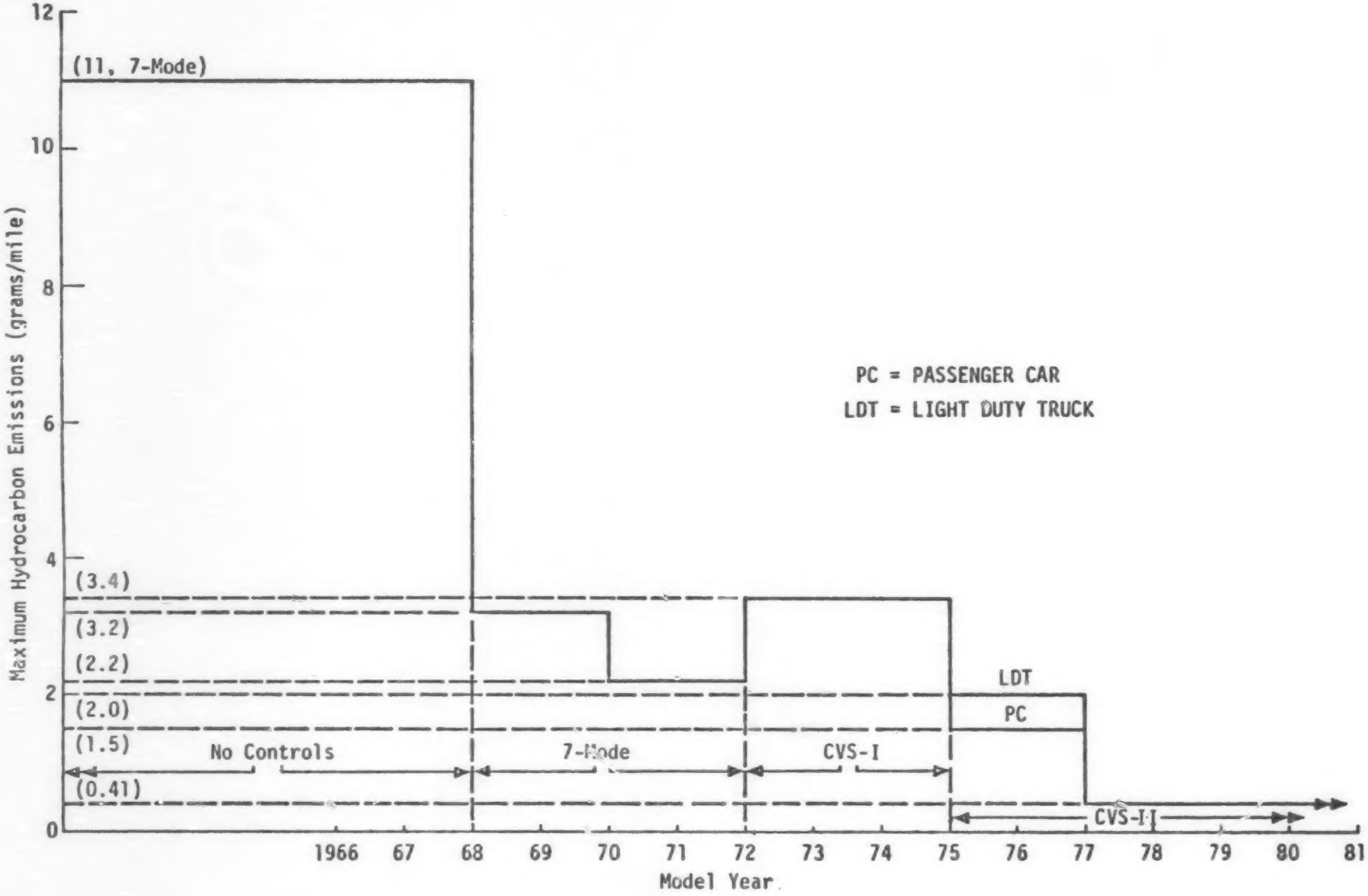
Evaporative emissions of hydrocarbons have been 6 gms/test for light-duty vehicles since 1970, and 2 gms/test since 1972. Heavy-duty gasoline-powered vehicles are 2 gms/test, effective 1973.

Source: California Air Resources Board (1974).



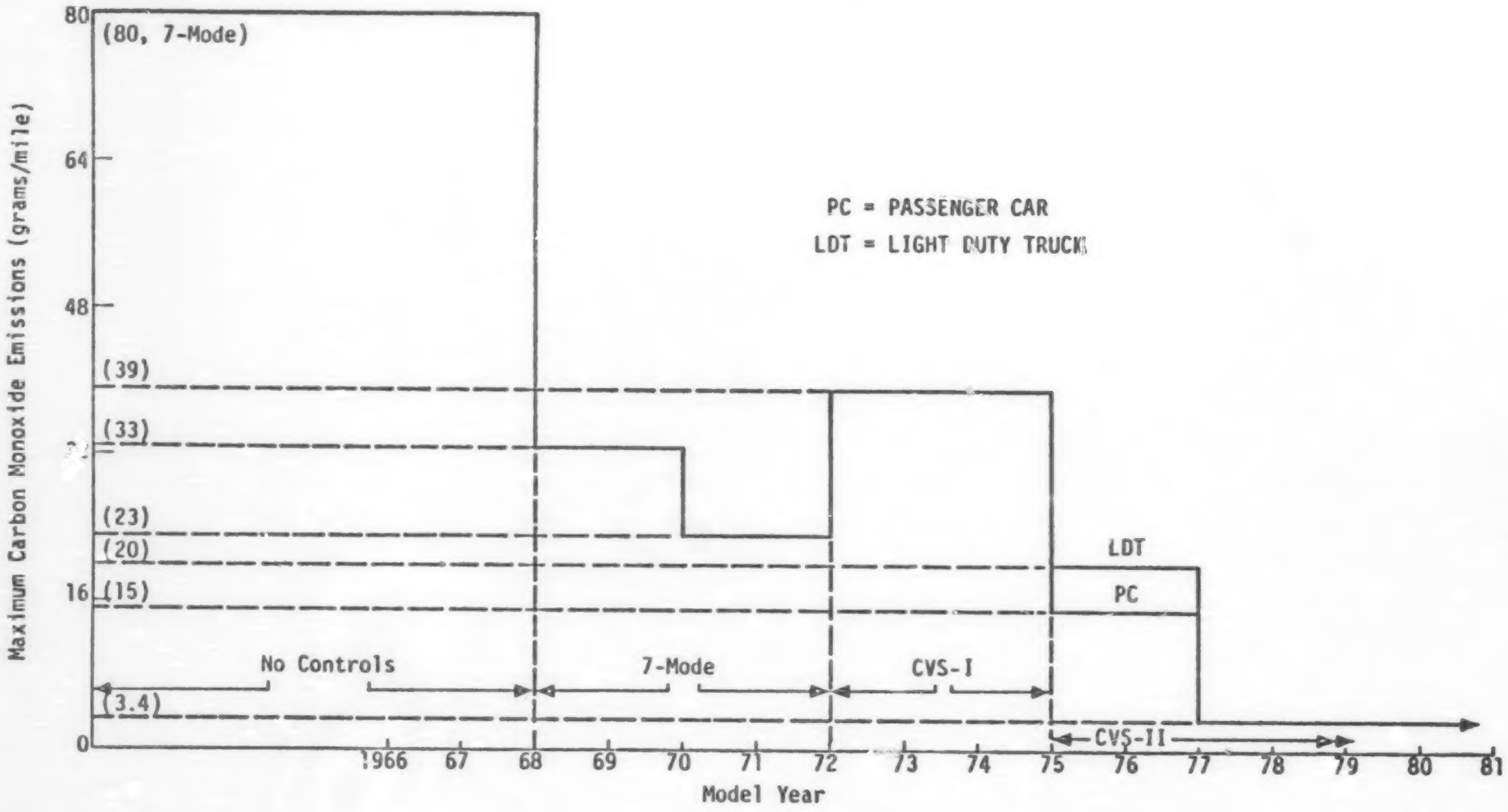
(a) Oxides of Nitrogen

FIGURE B-1. FEDERAL NEW VEHICLE EMISSIONS STANDARDS FOR LIGHT-DUTY VEHICLES



(b) Hydrocarbons

FIGURE B-1. (Continued)



(c) Carbon Monoxide

FIGURE B-1. (Concluded)

the Colorado Division of Highways is contained in the Detailed Assessment Report I-470 for the years 1985 and 2000. The source categories considered in these estimates were:

Point sources	(all pollutants)
Auto emissions	(all pollutants)
Gasoline service	(hydrocarbons)
Solvent users	(hydrocarbons)
Oil-based paint use	(all pollutants)
Space heating	(all pollutants)
Incinerators	(all pollutants)
Airports	(all pollutants)
Street sanding	(particulates)
Construction	(particulates).

Automobile and point source emissions are major emissions sources in the Denver metropolitan region. Automobiles account for roughly 80 percent of the hydrocarbon emissions, 30 to 40 percent of the nitrogen oxides emissions, 90 percent of the carbon monoxide emissions, and 10 to 15 percent of particulate emissions. Point sources account for roughly 15 to 20 percent of the hydrocarbon emissions, 40 to 50 percent of the nitrogen oxides emissions, and 10 to 15 percent of particulate emissions. Particulate emissions are largely from street sanding (45 to 60 percent) and construction (25 percent).

a. Automobile Emissions

Automobile emissions were estimated by the Colorado Department of Health and the Division of Highways in consultation with the EPA. Two separate files are used to estimate total automobile emissions. The Auto Link file accounts for automobile traffic that crosses traffic zone boundaries and the Auto Area (or Intrazonal VMT) file accounts for traffic that remains within traffic zone boundaries. The Link file alone accounts for more than 99 percent of the total automobile emissions for any pollutant.

The Link file was created by the Colorado Division of Highways using their transportation models. For the years 1974 and 1975 the input to these models was derived from traffic count data for the year 1971. For future years the inputs were derived from the year 2000 JRPP land use plan and the I-470 study. The DRCOG Empiric Activity Allocation Model was also used. Automobile emissions factors were estimated using AP-42, Supplement 5. Table B-2 summarizes the assumptions that were needed to estimate the emissions factors. Figure B-2 displays the variation, for winter and summer, in average CO emissions with the speed of operation of the "average" highway vehicle.

Since the emissions of pollutants from automobiles and other traffic are dependent on the typical cycles of operation, which vary with location and type of roadway, the Division of Highways classified the links in the Denver transportation system under eight roadway types and four area types. For the years 1985 to 2000, however, only five different roadway types were used in this classification system. Depending on whether the operating conditions are peak (rush-hour) or off-peak, the Division of Highways estimated average vehicle operating speeds for each of the roadway types within each area type. These estimates are summarized in Table B-3. Figure B-3 shows the estimated diurnal variation in traffic flow for the Denver metropolitan region and also indicates the hours of the day that are considered to be "peak" commute hours. In the summer, daylight savings time shifts the diurnal pattern one hour to the left.

Using the link node positions and lengths (inputs to the transportation models), the estimated average daily traffic (output of the transportation models), the estimated emission factors (as in Figure B-2) and the speed tables for the various link types (as in Table B-3), the Colorado Division of Highways estimated the Auto Link emissions as a function of the time of day and location within the Denver Highway Planning coordinate system. This Auto Link emissions file was created with the help of a special program, SAIEMIS, written by that division. The Auto Link emissions file, which incorporates hourly and seasonal

TABLE B-2. I-470 AIR QUALITY ANALYSIS

70% of vehicles are light-duty gas vehicles.
20% of vehicles are light-duty gas trucks.
0% of vehicles are light-duty diesel vehicles.
7% of vehicles are heavy-duty gas vehicles.
3% of vehicles are heavy-duty diesel vehicles.
0% of vehicles are motor cycles.

20% of the light-duty gas trucks and vehicles are operating from a cold start.*

27% of the light-duty gas trucks and vehicles are operating from a hot start.*

All heavy duty trucks and vehicles are operating hot.

Summer emission rates are based on 24° C (75° F).

Winter emission rates are based on -4° C (25° F).

Vehicle Age		Hourly Traffic Volume Factors, f(ADT)			
Percent	Age, Years	Hour	Factor	Hour	Factor
4.9	12 or more	1	.012	13	.053
2.2	11	2	.006	14	.058
2.8	10	3	.005	15	.064
3.9	9	4	.004	16	.078
5.4	8	5	.005	17	.101
6.6	7	6	.013	18	.090
6.9	6	7	.049	19	.058
8.7	5	8	.105	20	.038
10.3	4	9	.076	21	.030
10.6	3	10	.057	22	.030
11.9	2	11	.052	23	.027
15.4	1	12	.054	24	.020
10.4	0				

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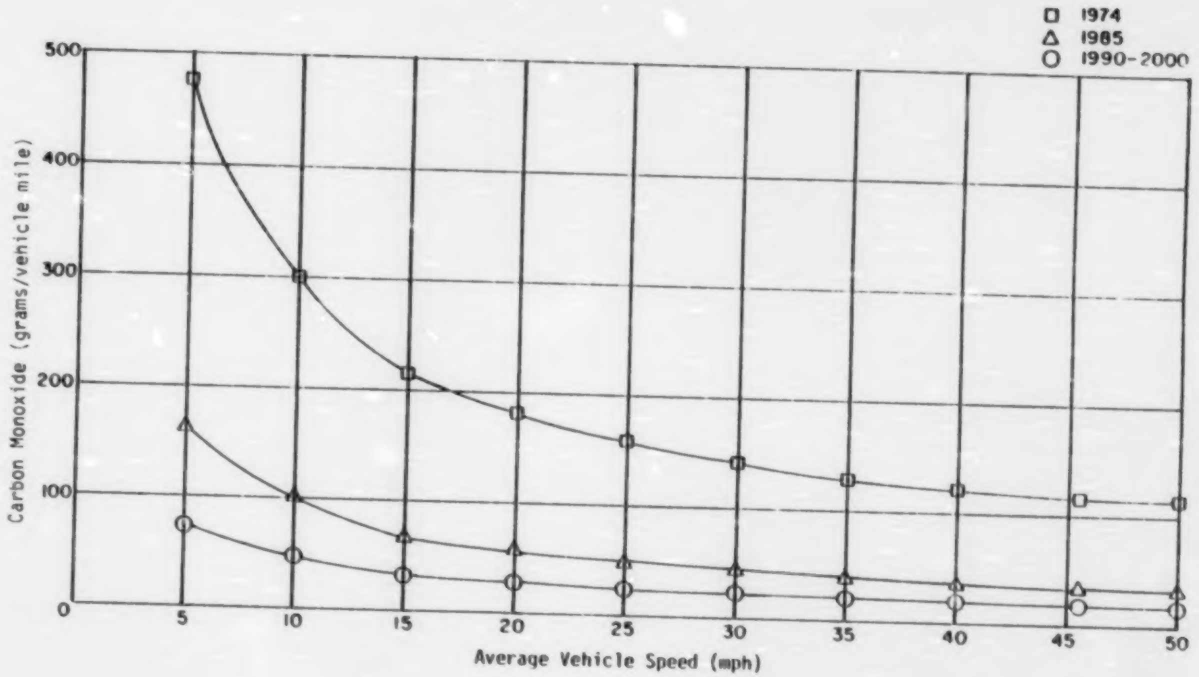
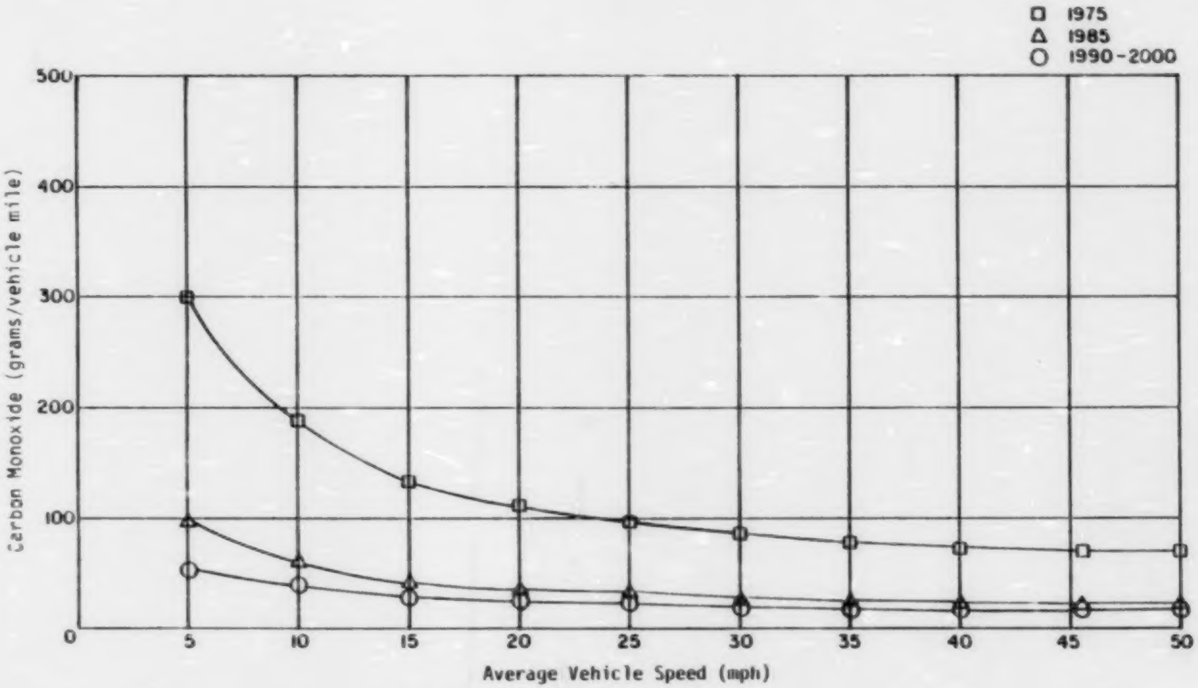
* The remainder of the vehicles (53%) are operating in a hot stabilized condition.

Source: Colorado Division of Highways (1976)



(a) Winter (Ambient temperature = 25° F.)

FIGURE B-2. VEHICLE EMISSIONS FACTORS USED IN THE DENVER MODEL



Source: Colorado Division of Highways (1976).

(b) Summer (Ambient temperature = 75° F.)

FIGURE B-2. (Concluded)

TABLE B-3. ESTIMATED OPERATING SPEEDS FOR TRAFFIC IN THE DENVER METROPOLITAN AREA BY ROADWAY AND AREA TYPES

(miles per hour)

Type of Roadway	Off-peak Period Speed				Peak Period Speed				Year
	CBD*	Fringe†	Residential§	Rural	CBD	Fringe	Residential	Rural	
Freeway	--	50	55	55	--	35	45	45	
Expressway	--	35	40	45	--	25	30	45	
Principal arterial	15	20	25	35	10	15	20	35	
Major arterial	15	20	25	35	10	15	20	35	
Minor arterial	15	20	25	35	1	15	20	35	1975
Collector	10	15	20	30	10	15	20	30	
Centroid connector	10	10	15	15	10	10	15	15	
Ramp	10	15	20	30	10	--	--	--	
Freeway	--	30	50	50	--	20	40	50	1985
Expressway	--	--	25	35	--	--	20	35	(used
All arterials	10	20	20	25	10	15	15	25	in
Collector	10	10	10	15	10	10	10	15	I-470
Centroid connector	10	10	15	15	10	10	15	15	study)
Freeway	--	25	50	50	--	20	40	50	
Expressway	--	--	--	--	--	--	--	--	2000
All arterials	10	20	25	30	10	15	20	30	(JRPP
Collector	10	10	15	20	10	10	15	20	plan)
Centroid connector	10	10	15	15	10	10	15	15	

---

* CBD = Central business district.

† Fringe = Fringe and outlying business area.

§ Residential = Residential and suburban.

Source: Mr. Rich Griffins, Colorado Division of Highways.

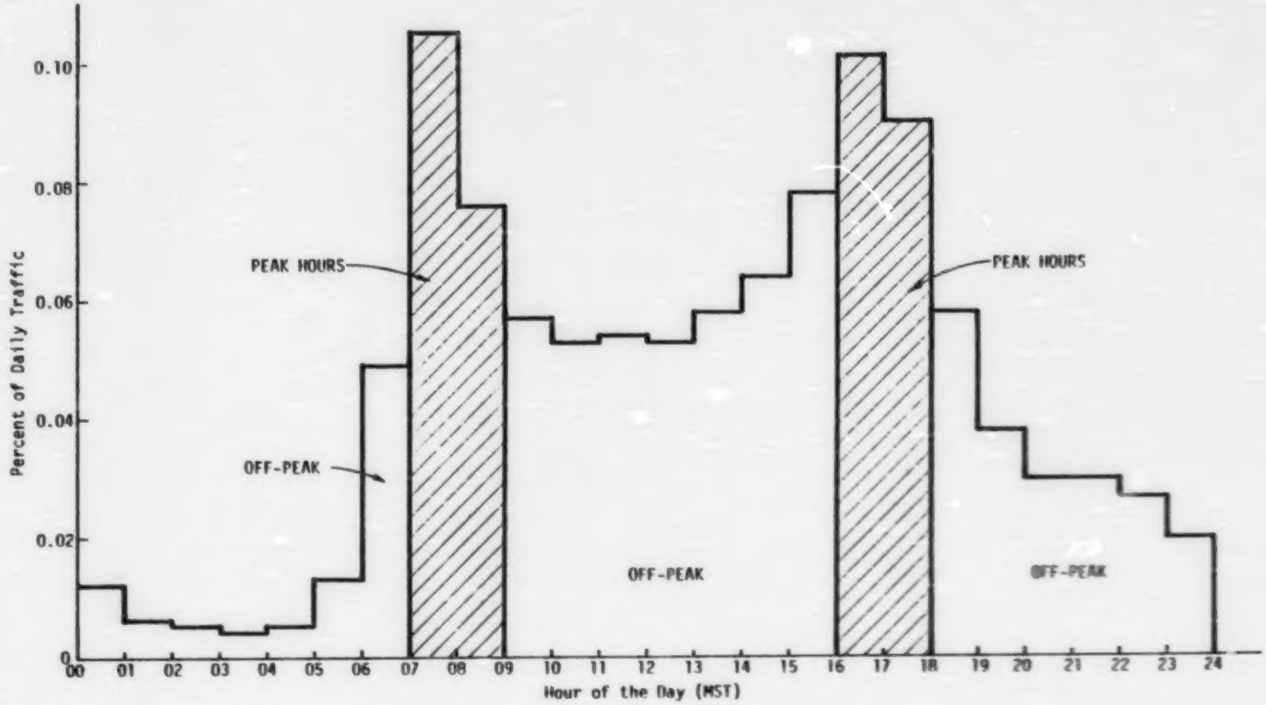


FIGURE B-3. DIURNAL TRAFFIC FLOW VARIATION IN THE DENVER METROPOLITAN REGION emission variations, may be input to the Denver Model. To create an input file for CDM, the inputs to SAIEMIS were first adjusted to reflect yearly average emission factors rather than seasonal (summer or winter) emissions; the output of SAIEMIS was further modified by a post-processor program to obtain average daily emissions that do not reflect the diurnal variations in traffic flow.

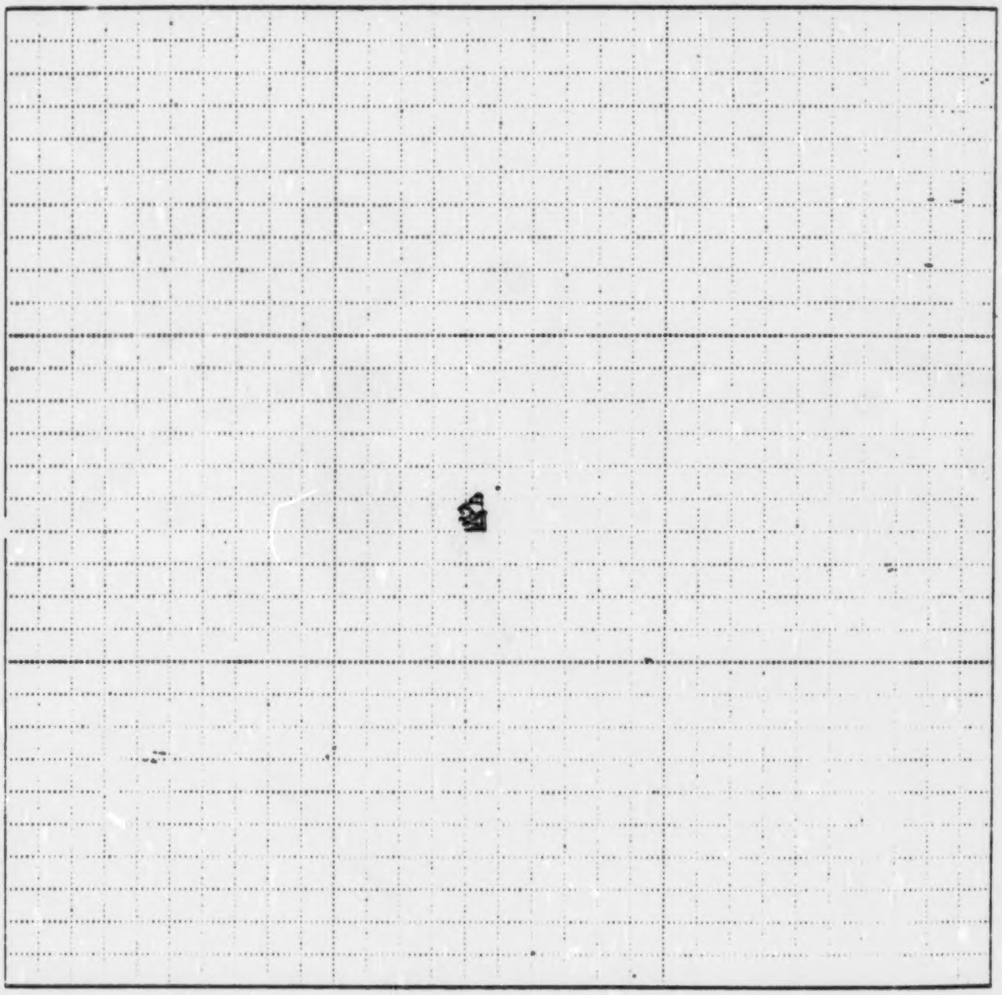
In order to present graphically some of the changes in land use anticipated between the years 1971 and 2000, we plotted the links that fall within each area type classification for both these years. These plots are presented in Figures B-4 through B-7. Figures B-4(a) and (b) show that the Central Business District comprises only a very small portion of the total area and increases only very slightly from 1971 to 2000. A comparison of Figures B-5(a) and (b) shows that the fringe and outlying business area are expected to develop significantly in the period from 1971 to 2000. Finally, Figures B-6(a) through B-7(b) show that a significant southward spreading of residential suburbs is expected at the expense of the rural area there. This development will also occur--although to a somewhat lesser extent--northward, westward, and eastward of Denver.

The procedure for determining the Auto Area emissions is outlined in the AQMA report of the Department of Health. Since these emissions account for less than one percent of the total auto emissions, we do not discuss this procedure here.

In treating auto emissions, the following assumptions were made:

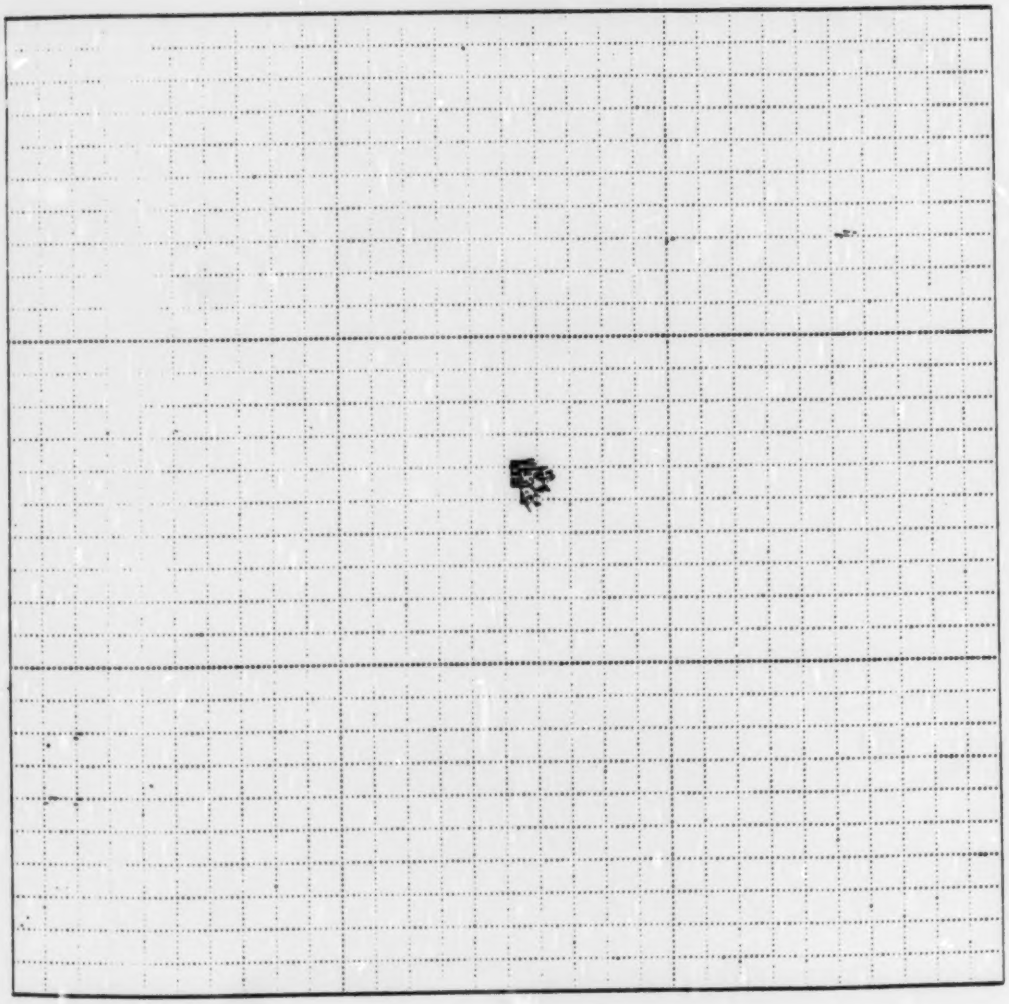
> By weight, 80 percent of the hydrocarbons emitted are reactive and 20 percent are unreactive.

> Nitrogen oxides are 85 percent by weight nitric oxide and 15 percent by weight nitrogen dioxide.



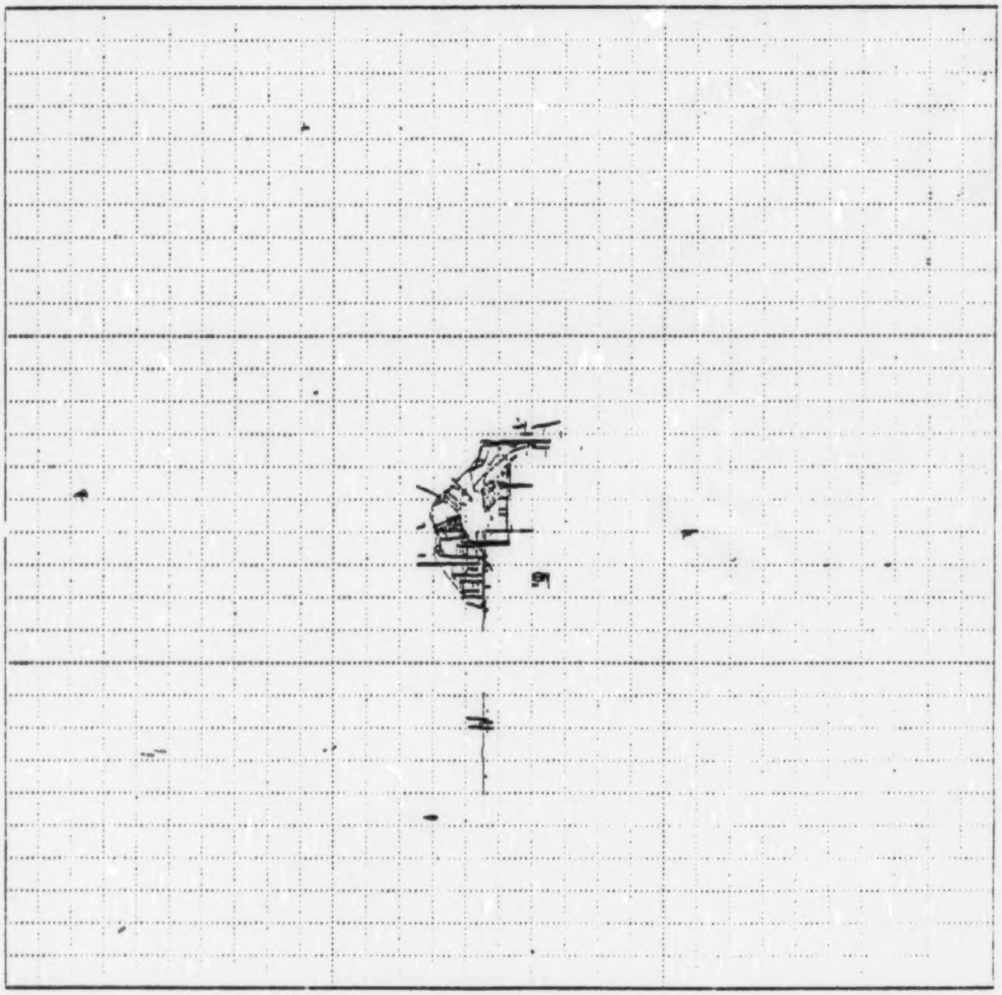
(a) Year 1971

FIGURE B-4. CENTRAL BUSINESS DISTRICT IN YEARS 1971 and 2000--ALL DENVER LINKS. The grid is of 1-mile squares.



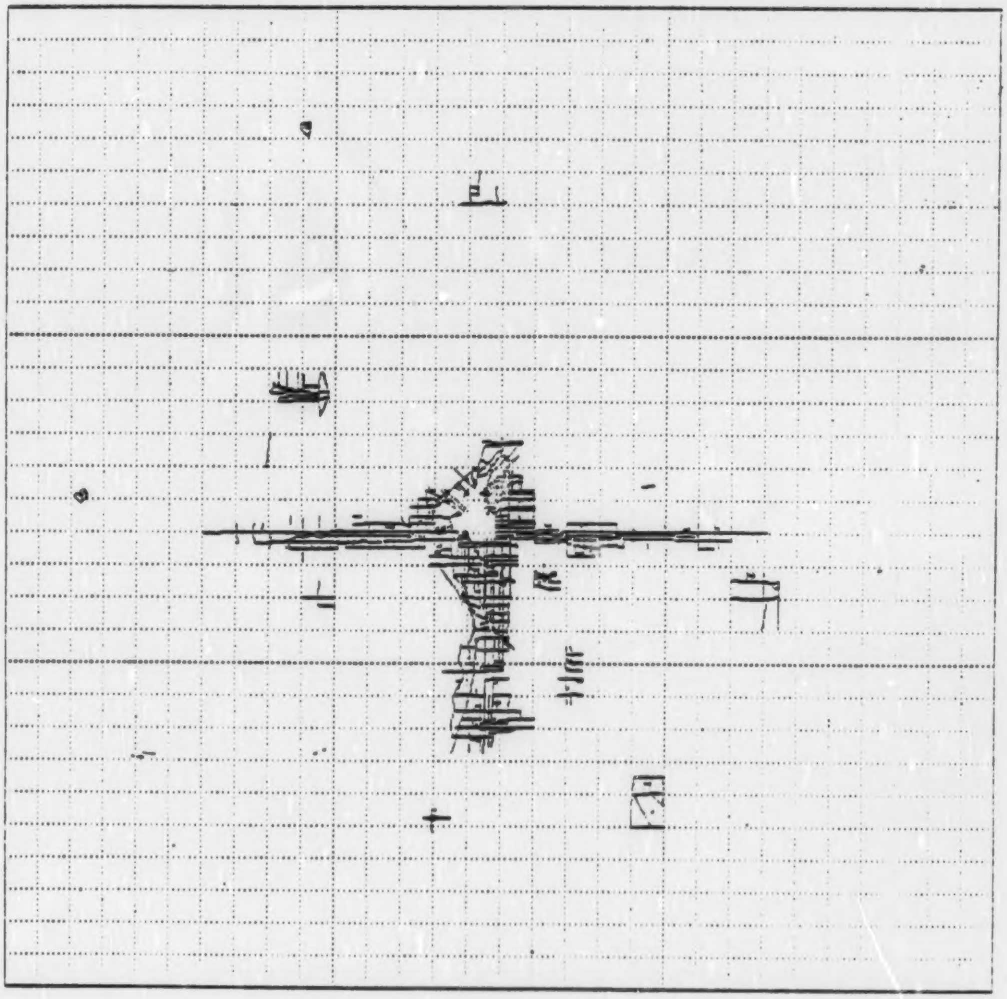
(b) Year 2000

FIGURE B-4. (Concluded)



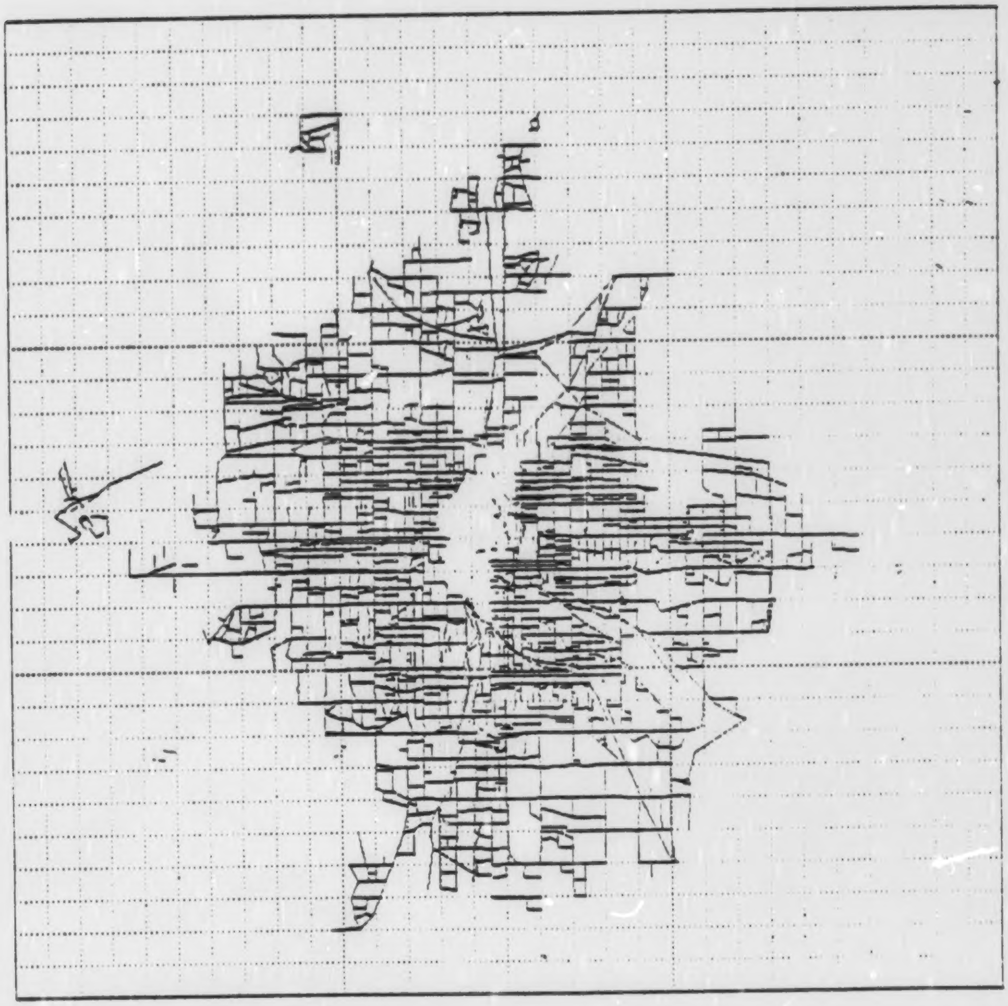
(a) Year 1971

FIGURE B-5. FRINGE AREA IN YEARS 1971 AND 2000--ALL DENVER LINKS. The grid is of 1-mile squares.



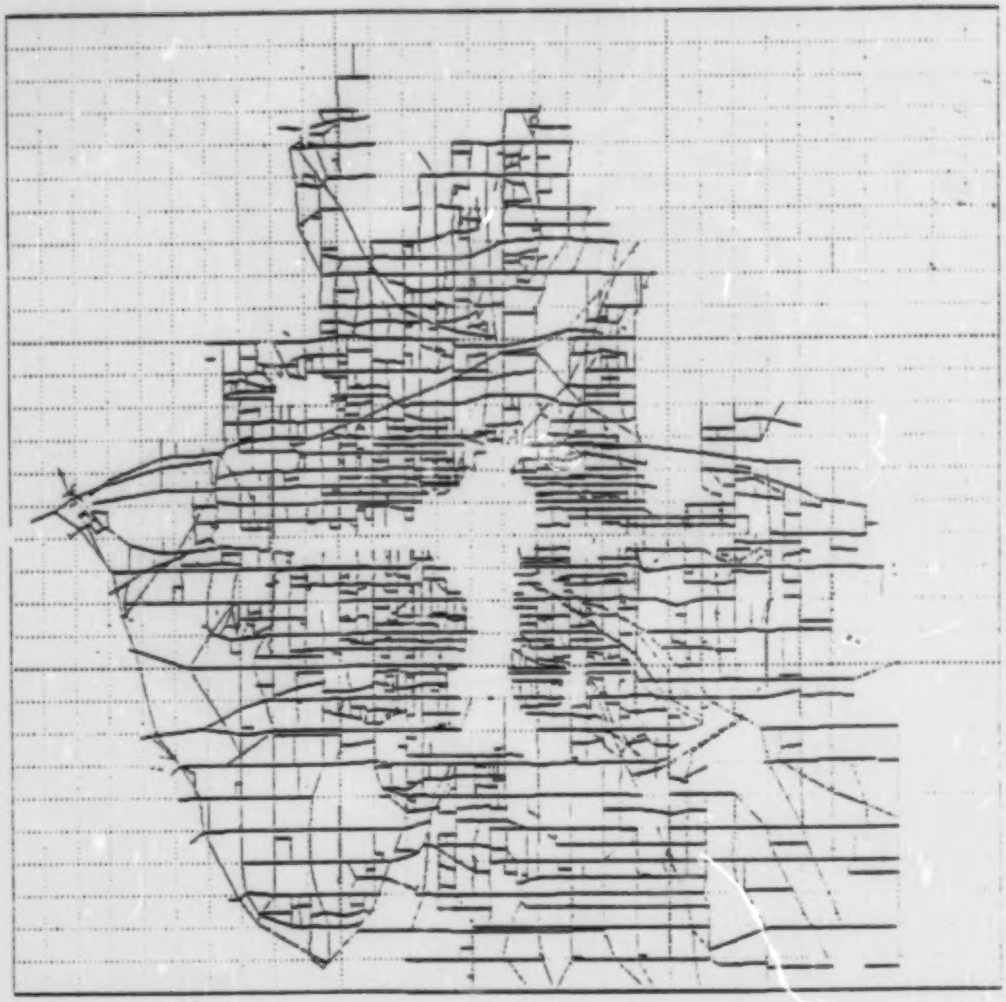
(b) Year 2000

FIGURE B-5. (Concluded)



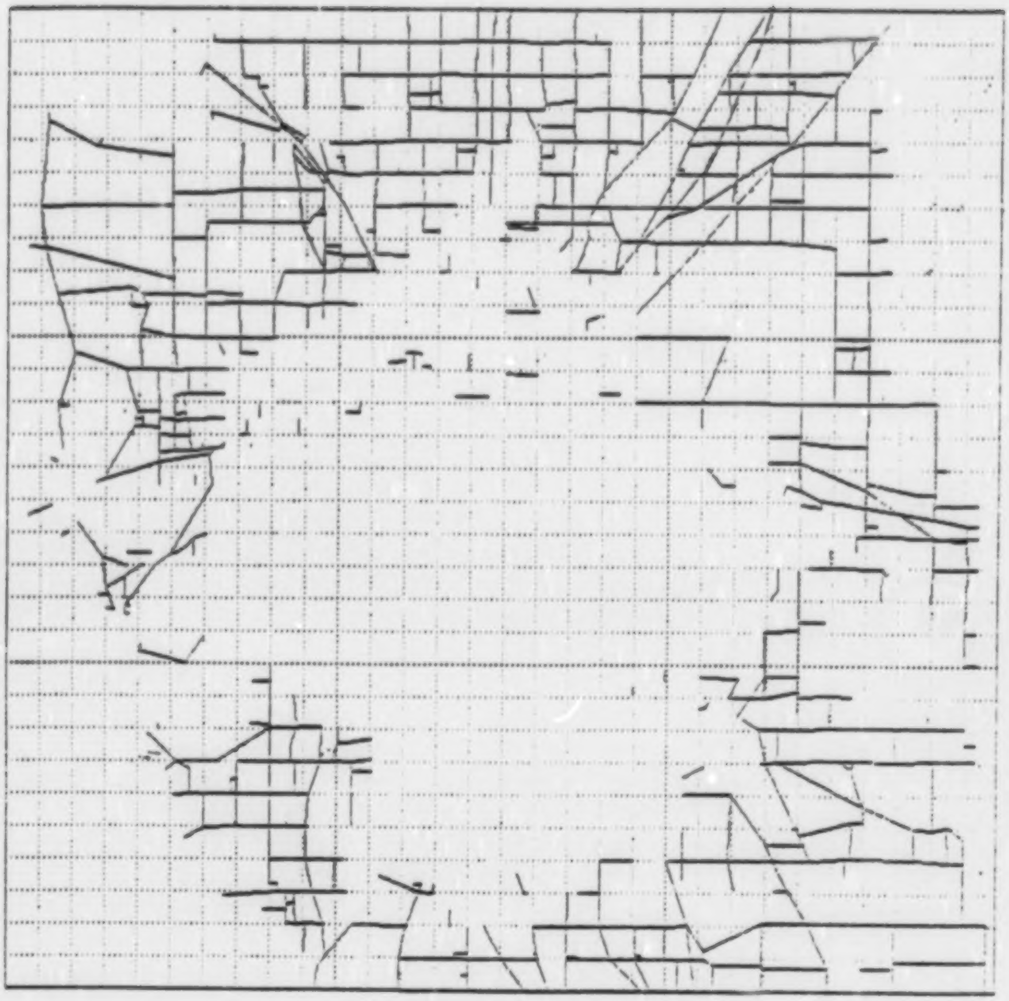
(a) Year 1971

FIGURE B-6. SUBURBAN AREA IN YEARS 1971 and 2000--ALL DENVER LINKS. The grid is of 1-mile squares.



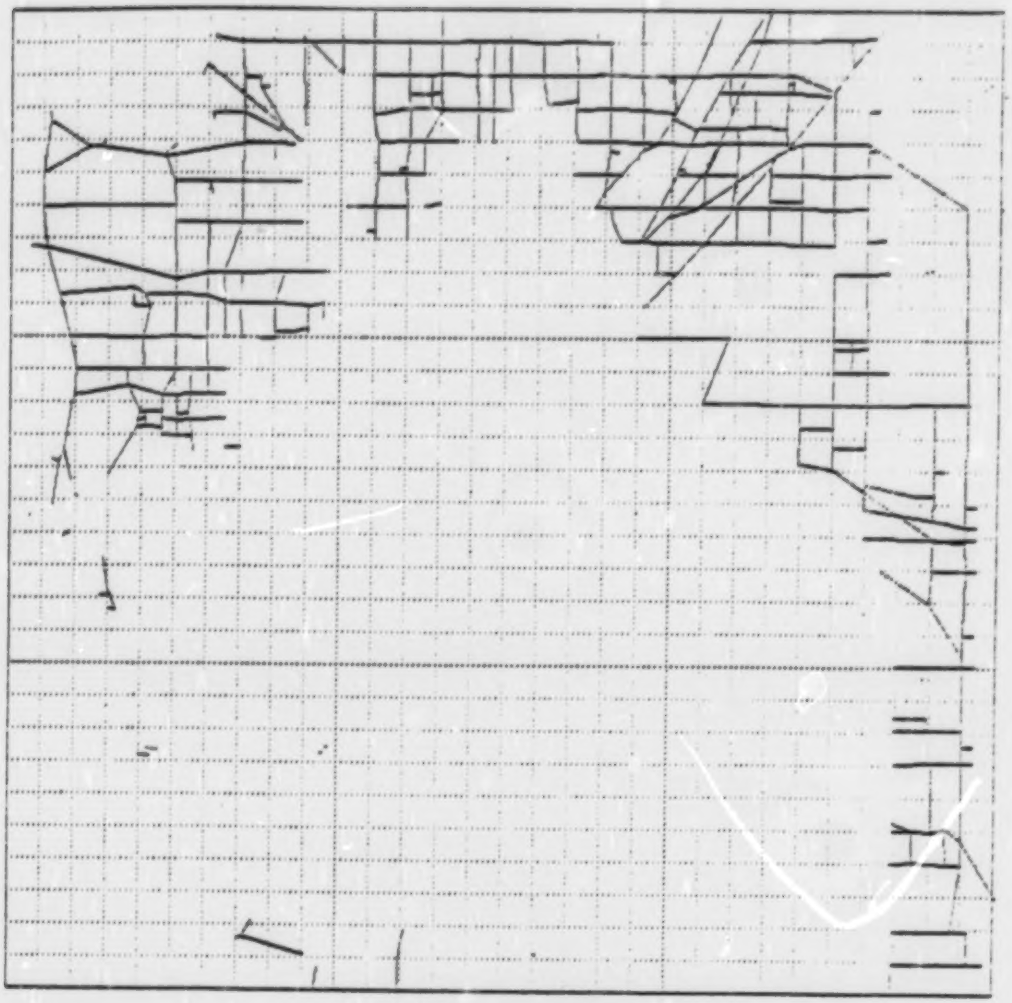
(b) Year 2000

FIGURE B-6. (Concluded)



(a) Year 1971

FIGURE B-7. RURAL AREA IN YEARS 1971 and 2000--ALL DENVER LINKS. The grid is of 1-mile squares.



(b) Year 2000

FIGURE B-7. (Concluded)

b. Emissions from Other Sources

As indicated above, point sources and such sources as street sanding and construction also contribute significantly to the overall emissions of pollutants in Denver. The major assumptions made in estimating the emissions from these and other sources are summarized in Table B-4.

4. ANALYSIS OF EMISSIONS INPUT TO CDM

The Climatological Dispersion Model accepts both point source emissions and area source emissions as inputs. The input emission rates must reflect annual averages. Inputs to the model include certain weighting factors to account for the differences in day/night emissions.

There were 171 point sources input to CDM and a number of area sources:

- > Auto area
- > Auto link
- > Airport
- > Construction
- > Street sanding
- > Space heating
- > Small point.

The emissions files used as inputs to CDM in this study were analyzed with the help of a specially written program to determine the trends in overall pollutant loading, the pollutant loading due to each source category, and the pollutant loading within each subregion designated for the sensitivity study.

Table B-5 presents the total emissions of particulates and nitrogen oxides (as nitrogen dioxide) for all modeling years considered here;

TABLE B-4. SUMMARY INFORMATION ON NONVEHICULAR SOURCES

Source Category	Assumptions and Comments	Sources of Information
Point Sources (general)	With the exception of emissions from the Cherokee Power Plant, emissions from existing point sources are assumed to remain unchanged from 1974 emissions levels.	Emissions Inventory Subsystem (EIS).
	Emissions from the Cherokee Power Plant for the years 1980 and beyond are assumed to be one-half of the 1974 emissions levels.	AP-42.
	Hydrocarbon emissions are assumed to be 75 percent reactive and 25 percent nonreactive. Nitrogen oxide emissions are assumed to be 85 percent by weight nitric oxide and 15 percent nitrogen dioxide.	DRCOG empiric four-cycle zonal allocations
	Point source projections are made on the assumption that increases in point source emissions are directly proportional to increases in the area of industrially zoned land.	
	There are a total of 171 point sources. All point sources are input to CDM, but for the Denver Model the largest sources are aggregated to form 46 sources. Plume rise is computed using modified forms of Holland's equation.	
Gasoline Service Stations	Emissions for 1974 were computed in proportion to the number of pumps.	State Department of Labor and Employment, Oil Inspection Section.
	Future emissions (1980, 1985) are assumed to increase in proportion to the increase in gasoline usage.	
	Phase I vapor recovery is assumed for future years (1980, 1985).	
Incinerators		AP-42.
		Source testing.
		Air Contaminant Emission Notice File.
Solvent Users	Solvent use changes are assumed to be proportional to population changes.	List of solvent users compiled by Enforcement Unit.
	Sources are primarily dry cleaners. Two types of solvents are considered--Perk and Stoddard.	DRCOG empiric four-cycle zonal allocations

TABLE B-4. (Continued)

Source Category	Assumptions and Comments	Sources of Information
Oil-based Paint Use	Consumption of oil paint is assumed to be proportional to population. Oil-based paint use in 1980 is assumed to be 50 percent of 1974 usage. No oil-based paint usage in 1985 and beyond.	Colorado Paint Manufacturers Association. DRCOG four-cycle empiric zonal allocations.
Space Heating	Residential gas use is directly proportional to population. Commercial gas use is directly proportional to the area of commercially zoned land. Industrial gas use by small industrial users is directly proportional to the area of industrially zoned land. Industrial gas use by large industrial users is unchanged through the years.	Public Service Company of Colorado. DRCOG four-cycle empiric zonal allocations.
Airports	The airports are Stapleton International, Arapahoe County, Jefferson County, and Buckley Air National Guard Base.	Environmental impact statements. FAA Master Records, (1974, 1975). AP-42. Traffic Control Center (Stapleton). *Aviation Forecasts Fiscal Years 1975-1986*, FAA Report. *Military Air Traffic Forecasts Fiscal Years 1975-1986*, FAA report.

TABLE B-4. (Concluded)

Source Category	Assumptions and Comments	Sources of Information
Street Sanding	0.17 lb/(vehicle-mile) emission factor (particulates)	Investigation of Fugitive Dust: Sources, Emissions and Control for Attainment of Ambient Air Quality Standards Colorado, PEDCO report.
	On 18 days per year dry sanded street conditions exist throughout the metropolitan area.	
	Seventy percent of the total VMT is on sanded streets.	
	Ninety percent of the average daily VMT occurs on the 18 "sand days."	
	Projections of street sanding emissions are based on growth in auto link VMT.	
Construction	Six months per year of active construction.	Investigation of Fugitive Dust: Sources, Emissions and Control for Attainment of Ambient Air Quality Standards Colorado, PEDCO report.
	Emissions of particulates are 0.8 tons/acre/month of active construction.	
	Rate of construction is proportional to the rate of change of total acres of land used for residential, commercial, and industrial purposes.	

TABLE B-5. TOTAL PARTICULATE AND NITROGEN OXIDE EMISSIONS INPUT TO THE CDM MODEL

Emissions	Year 1974	1980	1985	1990	2000
Particulate emissions					
Tons per day	88	106	130	152.6	157.6
Increase over 1974 emissions	--	20%	48%	73%	79%
Nitrogen oxide emissions (as NO_2)					
Tons per day	180	213	241	245	262
Increase over 1974 emissions	--	18%	34%	36%	46%

the table shows that particulate emissions tend to rise relatively faster than do the nitrogen oxide emissions over the period from 1971 to 2000. Figure B-8 shows the changes in emissions over this period; the yearly increase of nitrogen oxide emissions is much lower in the period from 1985 to 2000 than in the period from 1974 to 1985. There is a similar lowering in the rate of increase of particulate emissions over the period from 1990 to 2000.

Table B-6 presents the particulate emissions from the point sources and the various source categories for which separate files were created. In Figure B-9 the year-to-year variation in total emissions from each source category is plotted and in Figure B-10 the percentage contribution from each source category is plotted. Street sanding and construction can be seen to be major sources of particulates; large point sources and auto link emissions account for most of the remaining particulate emissions. It must be noted that there appears to be a rather large and sudden increase in emissions from the "space heating plus construction" category in the period from 1985 to 1990. The estimates of emissions up to and including the year 1985 were made by the Department of Health (Air Pollution Control Division), and the estimates for the years 1990 and 2000 were made by the Colorado Division of Highways. The abrupt change in estimated construction and space heating emissions could be due to some difference in the estimation methodologies used by these independent groups. A somewhat similar but less abrupt change in street sanding emissions is also evident.

The nitrogen oxides emissions were also analyzed by source category; these data are presented in Table B-7 and Figures B-11 and B-12. Auto link and large point emissions account for the major part of the emissions. Space heating and small point sources also emit considerable quantities of nitrogen oxides. There again appears to be a rather marked change in the year-to-year trend in emissions over the period from 1985 to 1990 for the space heating and auto link emissions categories. As before, this change could result from differences

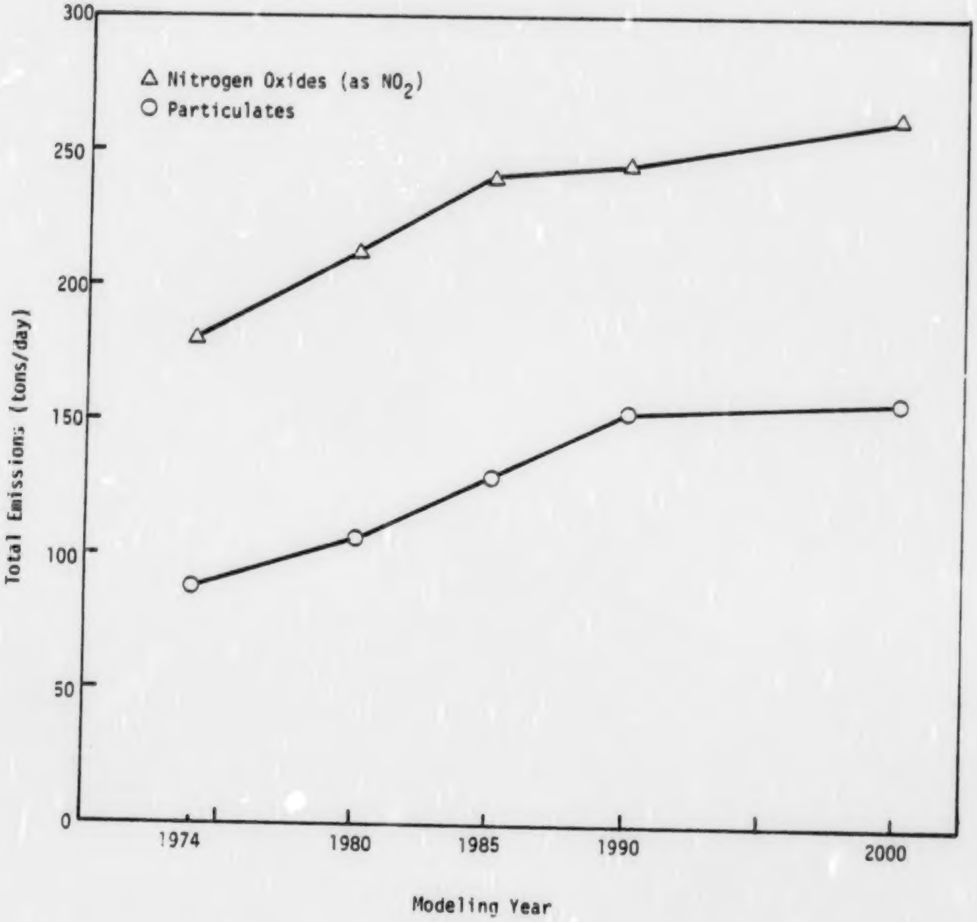


FIGURE B-8. TOTAL EMISSIONS OF NO_2 AND PARTICULATES INPUT TO THE CLIMATOLOGICAL DISPERSION MODEL

TABLE B-6. PARTICULATE EMISSIONS FROM SOURCE CATEGORIES AS INPUT TO THE CDM MODEL. A = tons per day, B = percent of total.

	1974		1980		1985		1990		2000	
Source Category	A	B	A	B	A	B	A	B	A	B
Auto area	0.0823	0.094%	0.0377	0.036%	0.0591	0.045%	0.0591	0.039%	0.0539	0.034%
Auto link	10.4	11.8	11.1	10.5	13.9	10.7	14.1	9.2	15.1	9.5
Airport	0.156	0.18	0.326	0.31	0.188	0.14	0.22	0.14	0.253	0.16
Street sanding	39.4	44.8	56.4	53.2	81.2	62.5	80.6	52.8	86.2	54.7
Space heating	1.27	1.4	1.57	1.5	1.69	1.3	*	*	*	*
Construction	21.7	24.7	21.7	20.5	17.4	13.4	*	*	*	*
Space heating plus construction	23.0	26.1	23.3	22.0	19.1	14.7	41.9	27.5	40.5	25.7
Small point	0.233	0.26	2.27	2.1	3.68	2.8	3.68	2.4	3.68	2.3
Large point	14.6	16.6	12.3	11.6	12.3	9.5	12.3	8.1	12.3	7.8
Total	88	99.9	106	99.7	130	100.4	152.6	100.1	157.6	100.3

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* For the years 1990 and 2000, space heating and construction emissions were lumped together; their total is therefore also shown for prior modeling years.

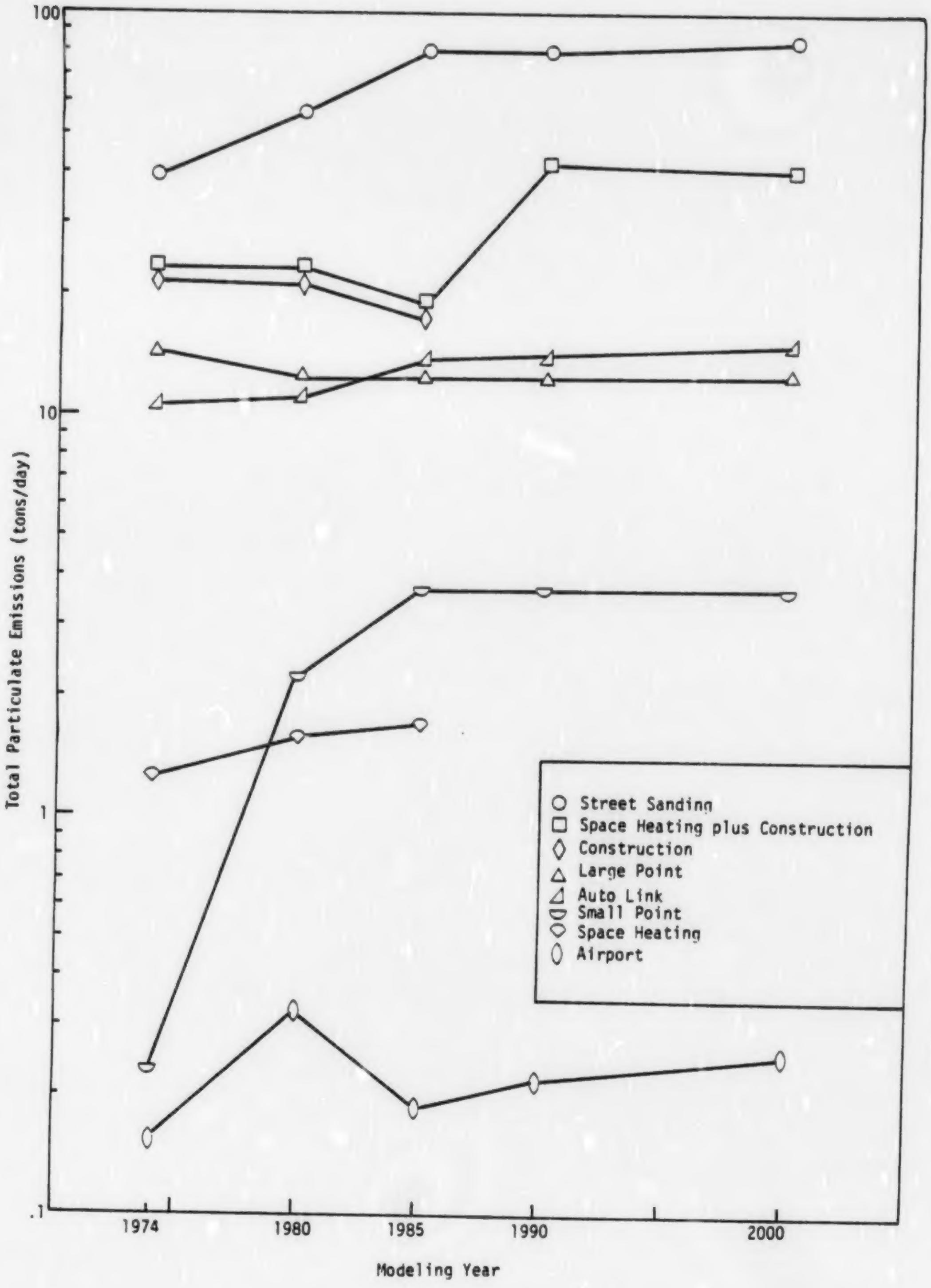

FIGURE B-9. PARTICULATE EMISSIONS FROM SOURCE CATEGORIES INPUT TO THE CDM MODEL

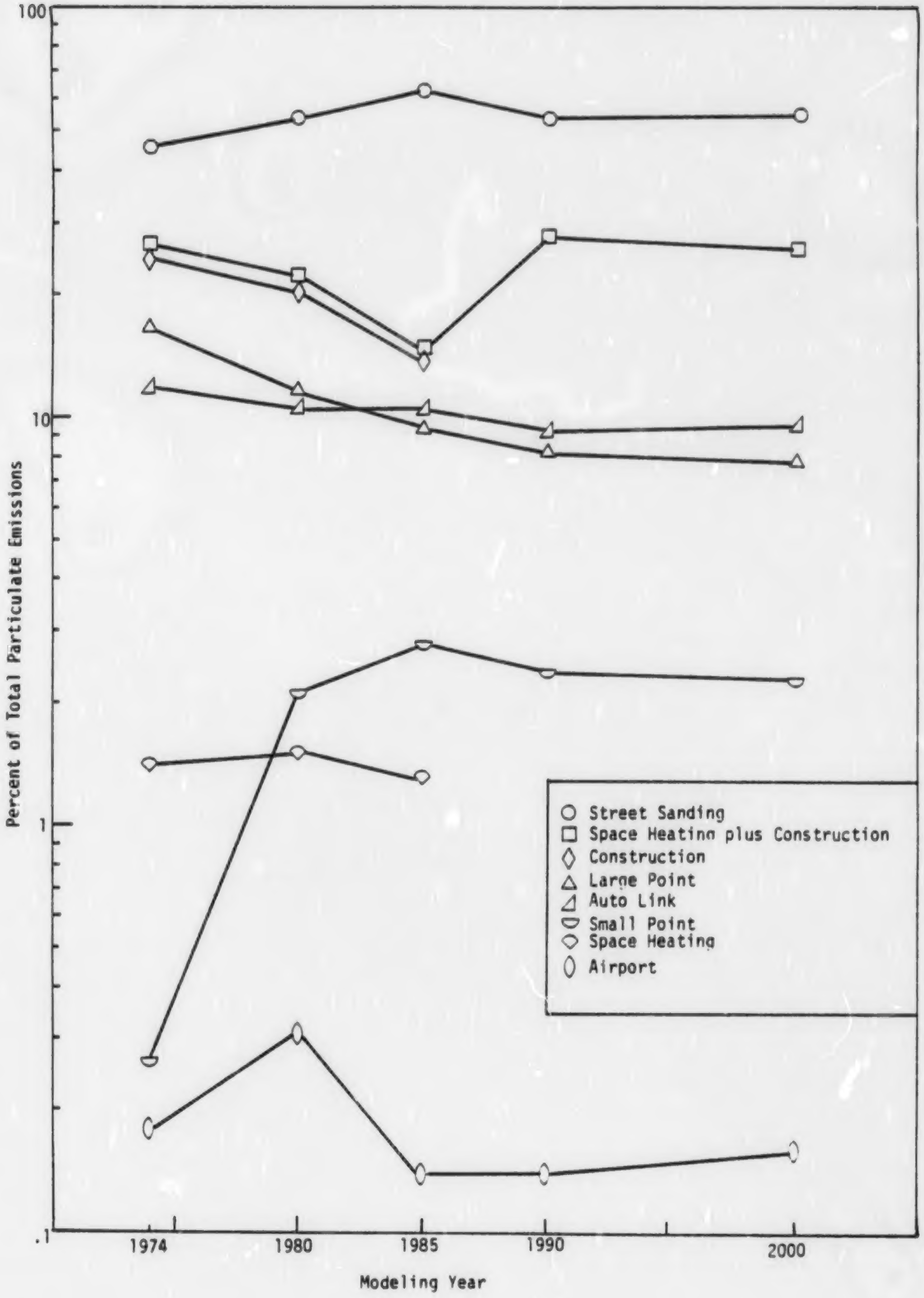

FIGURE B-10. PERCENTAGE CONTRIBUTION OF SOURCE CATEGORIES TO PARTICULATE EMISSIONS

TABLE B-7. NITROGEN OXIDE EMISSIONS (AS NO_2) FROM SOURCE CATEGORIES AS INPUT TO THE CDM MODEL. A = tons per day, B = percent of total.

	1974		1980		1985		1990		2000	
Source Category	A	B	A	B	A	B	A	B	A	B
Auto area	0.523	0.29%	0.313	0.15%	0.476	0.20%	0.476	0.19%	0.351	0.13%
Auto link	78.2	43.4	99.9	46.9	120	49.8	10.5	42.9	114	43.5
Airport	3.86	2.1	4.57	2.1	5.23	2.2	6.12	2.5	7.04	2.7
Street sanding	0	0	0	0	0	0	0	0	0	0
Space heating	13.3	7.4	16	7.5	17.2	7.1	35.5	14.5	42.1	16.1
Construction	0	0	0	0	0	0	0	0	0	0
Small point	1.216	0.12	8.58	4.0	14.4	6.0	14.4	5.9	14.4	5.5
Large point	84	46.7	84	39.4	84	34.0	84	34.3	84	32.1
Total	180	100	213	100	241	100.2	245	100.3	252	100

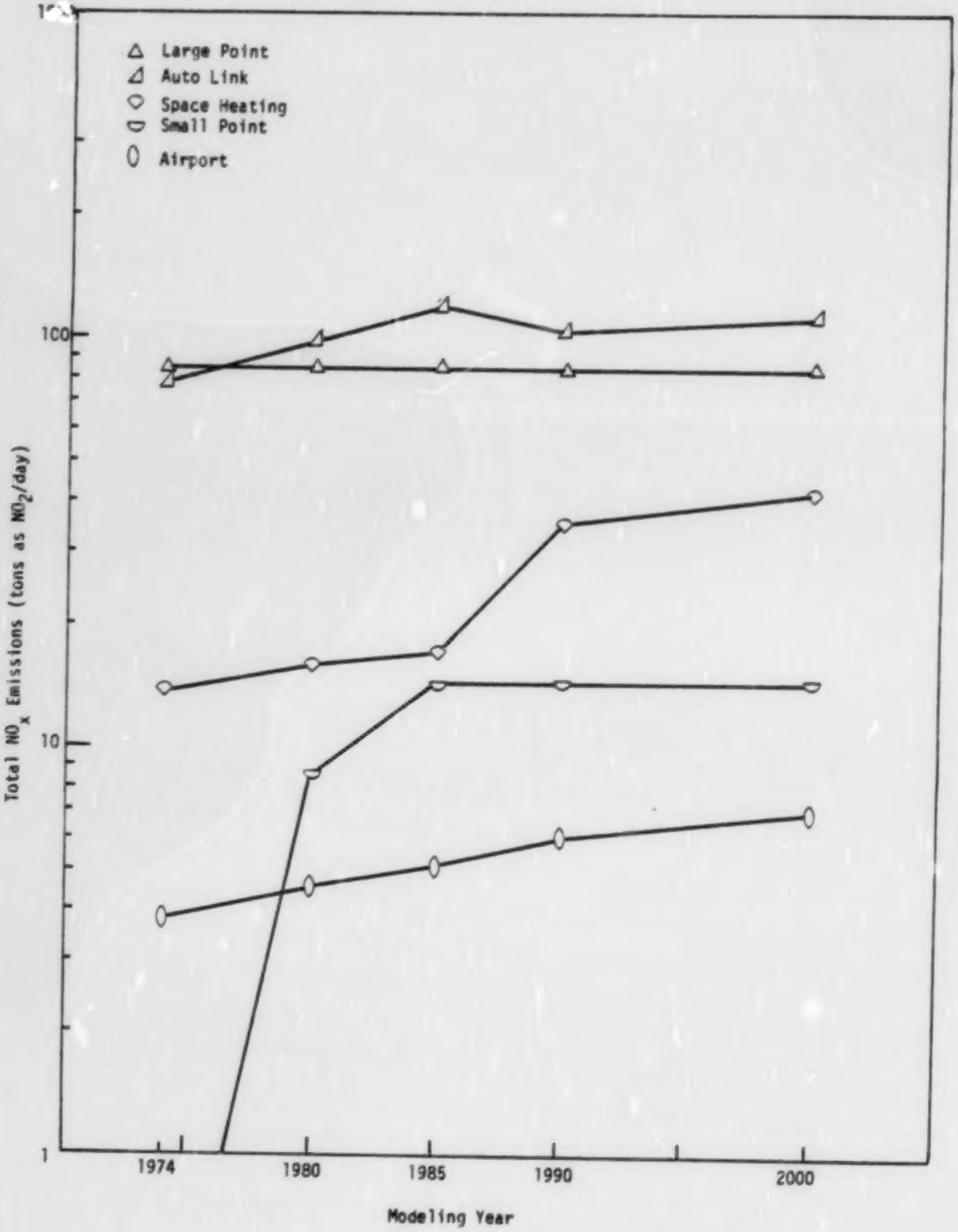

FIGURE B-11. NITROGEN OXIDE EMISSIONS FROM SOURCE CATEGORIES INPUT TO THE CDM MODEL

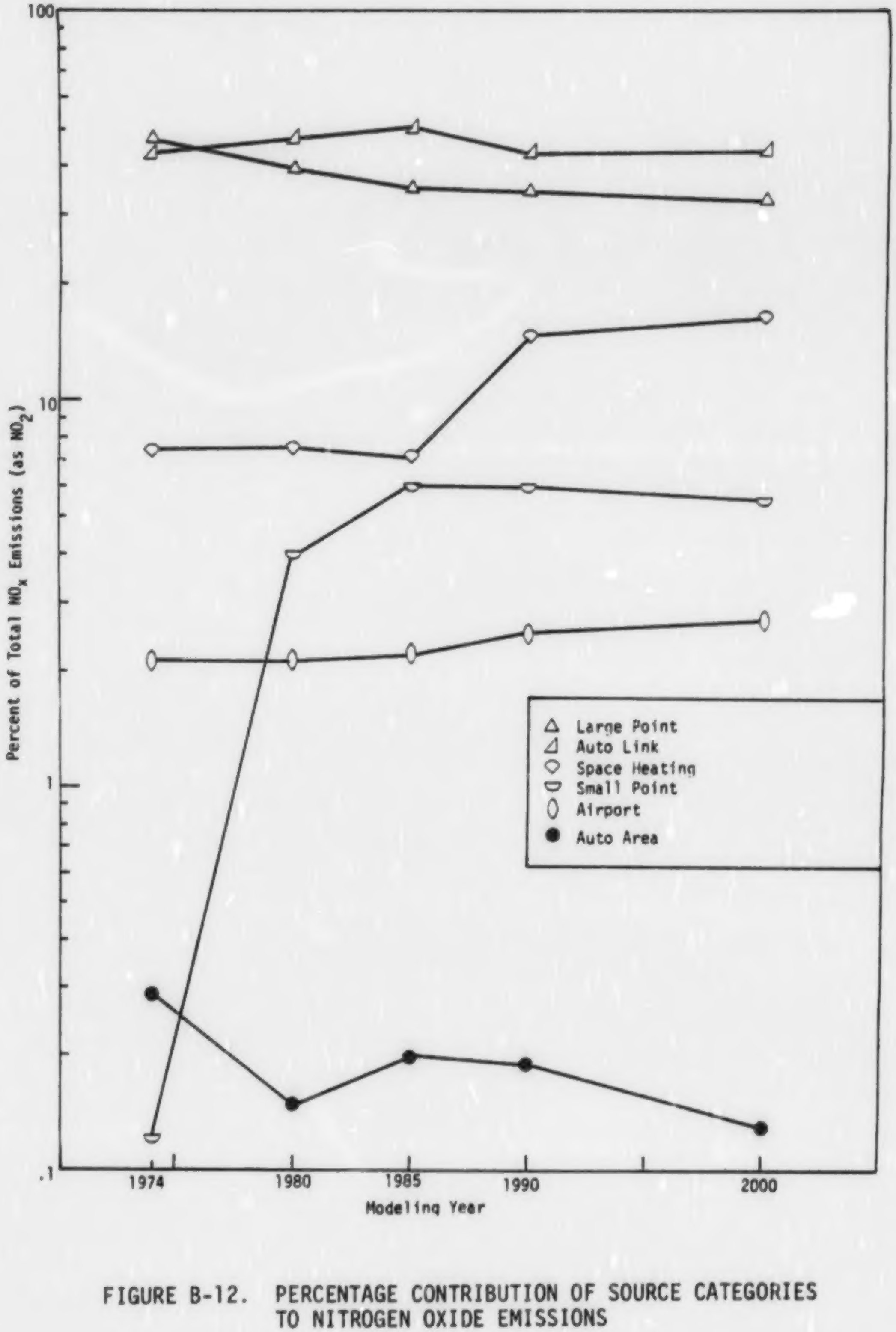

FIGURE B-12. PERCENTAGE CONTRIBUTION OF SOURCE CATEGORIES TO NITROGEN OXIDE EMISSIONS in the estimation methodologies used by the Health Department and the Division of Highways.

Both the particulate emissions and the nitrogen oxides emissions were further analyzed to determine how much of each of these pollutants is emitted within each of the seven subregions delineated in the sensitivity study and also in the surrounding area. There results are presented in Tables B-8 and B-9 and Figures B-13 through B-16. The majority of pollutants are emitted in Central Denver and in the "outer" subregion (due to the large total area of this subregion). In the case of the oxides of nitrogen, more than 50 percent of the total emissions are emitted outside the seven subregions chosen for the sensitivity study. This is largely due to the fact that 90 percent of the large point emissions lie outside the seven subregions. Finally, note that even though the emissions in the relatively small subregions such as South Metro and Jeffco-Urban rise comparatively rapidly, they still account for less than a few percent of the total emissions even in the year 2000.

Another simple set of calculations for studying how the emissions of pollutants vary from year to year within each of the subregions is to study the density of emissions (or emissions flux) within each subregion. Table B-10 indicates the total land area covered by each subregion. Using this table and data on total emissions within each subregion, the emissions fluxes were computed and are presented in Tables B-11 and B-12 and Figures B-17 and B-18. Emissions fluxes increase in all the subregions but the rate of increase is relatively rapid in some of the currently less developed areas, such as Jeffco-Urban and Metro. Furthermore, there appears to be some decrease in the overall range of emissions fluxes as development of land spreads outward from Central Denver.

5. ANALYSIS OF EMISSIONS INPUT TO THE DENVER MODEL

Since the Denver Model predicts concentrations of reactive pollutants and is used for short-term averages, its emissions input

TABLE B-8. PARTICULATE EMISSIONS IN SUGREGIONS AS INPUT TO THE CDM MODEL. A = tons per day, B = percent of total.

	1974		1980		1985		1990		2000	
Subregion	A	B	A	B	A	B	A	B	A	B
1 Outer	32.6	37.0%	37.1	35.0%	47.1	36.2%	51.6	33.7%	51.2	32.4%
2 Broomfield-Westminster-Arvada	6.18	7.0	7.88	7.4	9.65	7.4	10.8	7.1	12.2	7.7
3 Northglenn-Thornton	2.84	3.2	3.81	3.6	4.58	3.5	5.99	3.9	6.14	3.9
4 Aurora	4.91	5.6	6.13	5.8	7.68	5.9	9.37	6.1	10.5	6.6
5 South Metro	3.4	3.9	4.37	4.1	6.58	5.1	8.13	5.3	7.91	5.0
6 Jeffco-Urban	1.18	1.3	1.51	1.4	3.53	2.7	8.73	5.7	9.49	6.0
7 Lakewood	6.62	7.5	8.08	7.6	9.43	7.3	12.3	8.0	12.5	7.9
8 Central Denver	30.2	34.3	36.9	34.8	41.9	32.2	45.9	30	48.2	30.5
Total	88	99.8	106	99.7	130	100.3	153	99.8	158	100

TABLE B-9. NITROGEN OXIDE EMISSIONS (AS NO_2) IN SUBREGIONS AS INPUT TO THE CDM MODEL. A = tons per day, B = percent of total.

Subregion	1974		1980		1985		1990		2000	
	A	B	A	B	A	B	A	B	A	B
1 Outer	103	57.2%	115	54.0%	126	52.3%	131	53.5%	132	50.4%
2 Broomfield-Westminster-Arvada	7.41	4.1	9.79	4.6	12.2	5.1	12.9	5.3	14.5	5.5
3 Northglenn-Thornton	3.44	1.9	5.01	2.4	6.13	2.5	6.64	2.7	7.4	2.8
4 Aurora	4.14	2.3	6.14	2.9	8.37	3.5	9.02	3.7	10.3	3.9
5 South Metro	2.39	1.3	4.7	2.2	8.42	3.5	8.19	3.3	8.77	3.3
6 Jeffco-Urban	0.631	0.4	1.29	0.6	3.88	1.6	4.39	1.8	6.12	2.3
7 Lakewood	7.93	4.4	10.2	4.8	11.8	4.9	12	4.9	14.4	5.5
8 Central Denver	51.6	28.7	60.9	28.6	63.8	26.5	61.3	25	68.3	26.1
Total	180	100.3	213	100.1	241	99.9	245	100.2	262	99.8

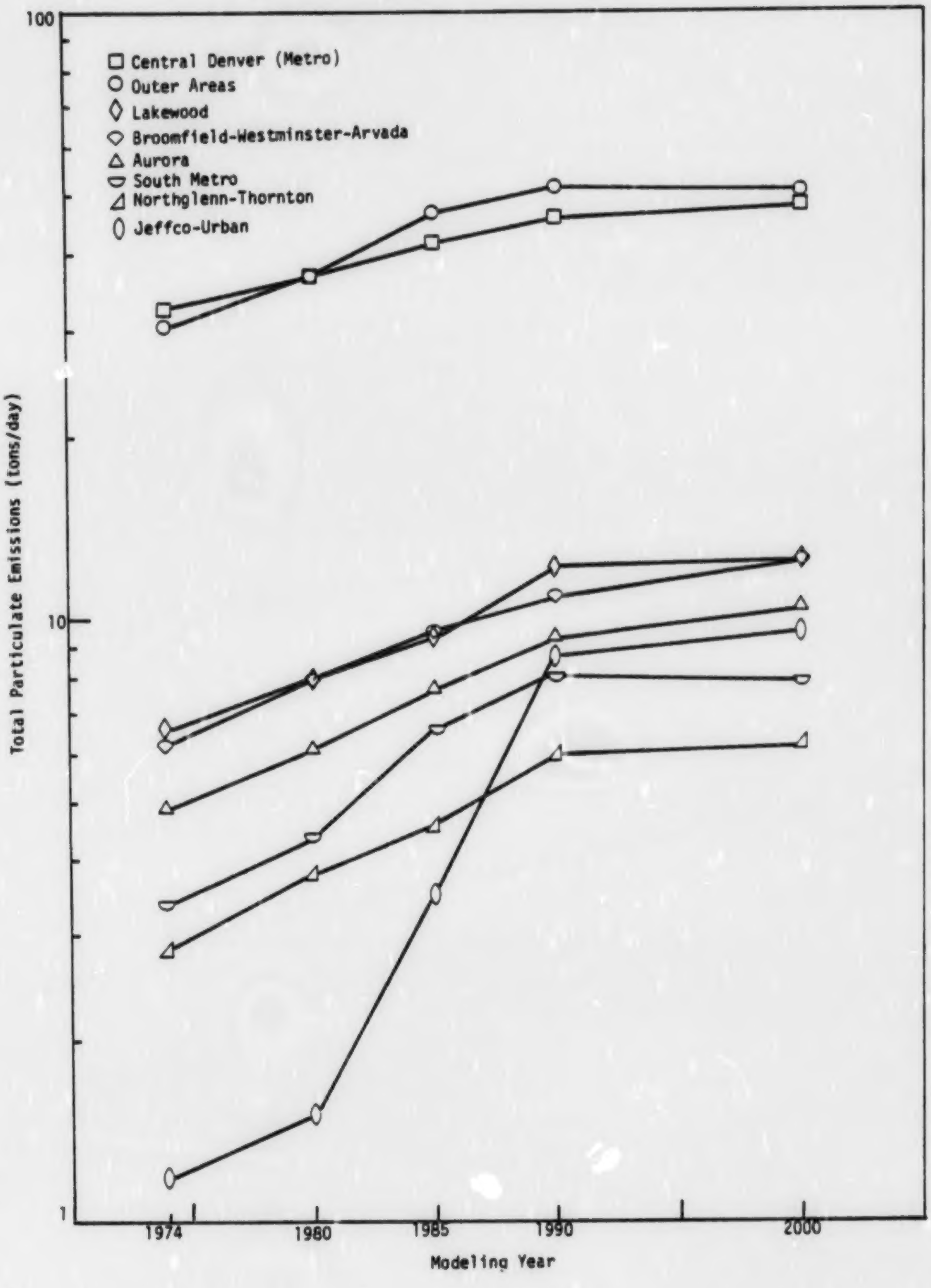

FIGURE B-13. PARTICULATE EMISSIONS IN SUBREGIONS INPUT TO THE CDM MODEL

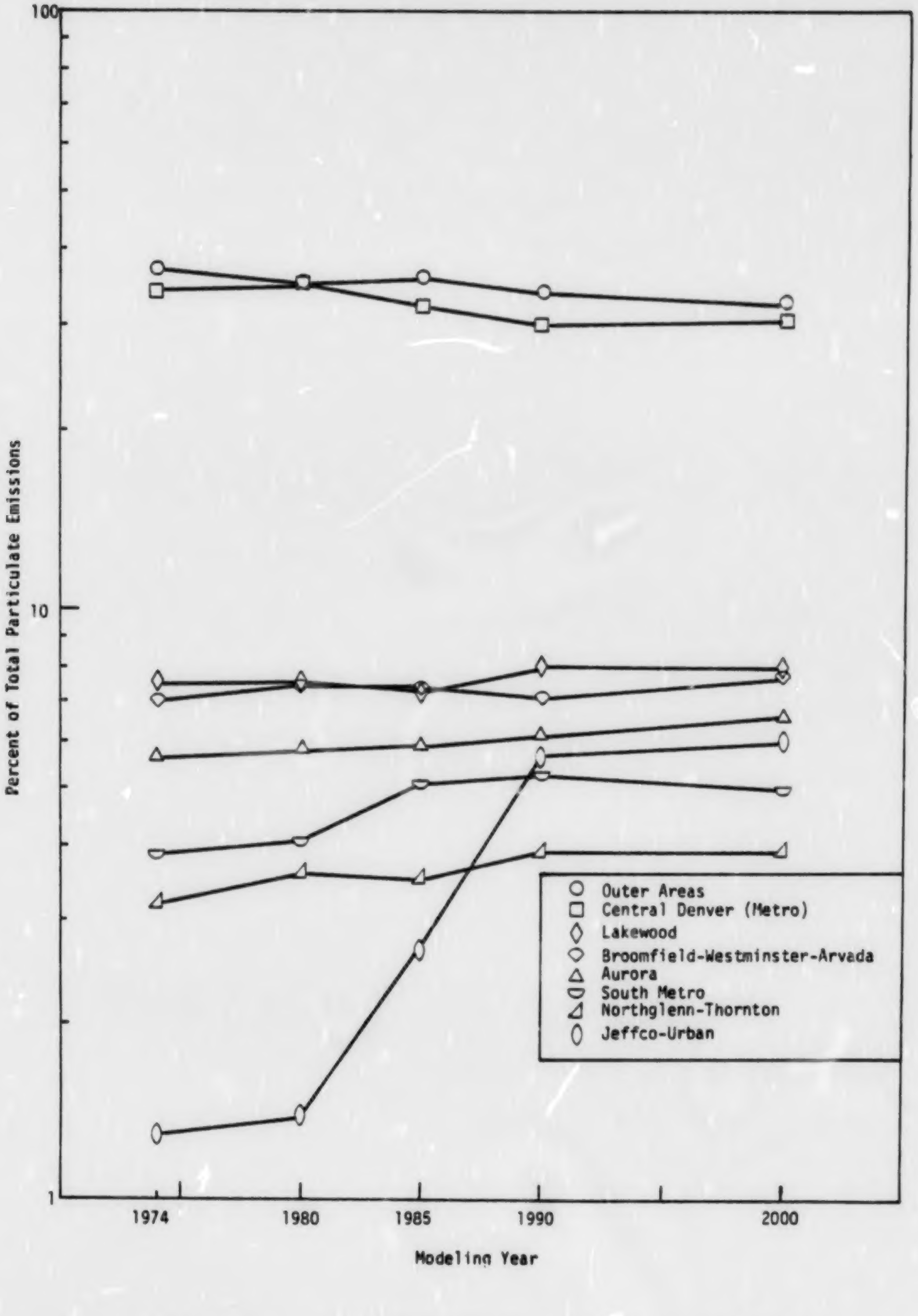

FIGURE B-14. PERCENTAGE CONTRIBUTION OF SUBREGIONS TO PARTICULATE EMISSIONS

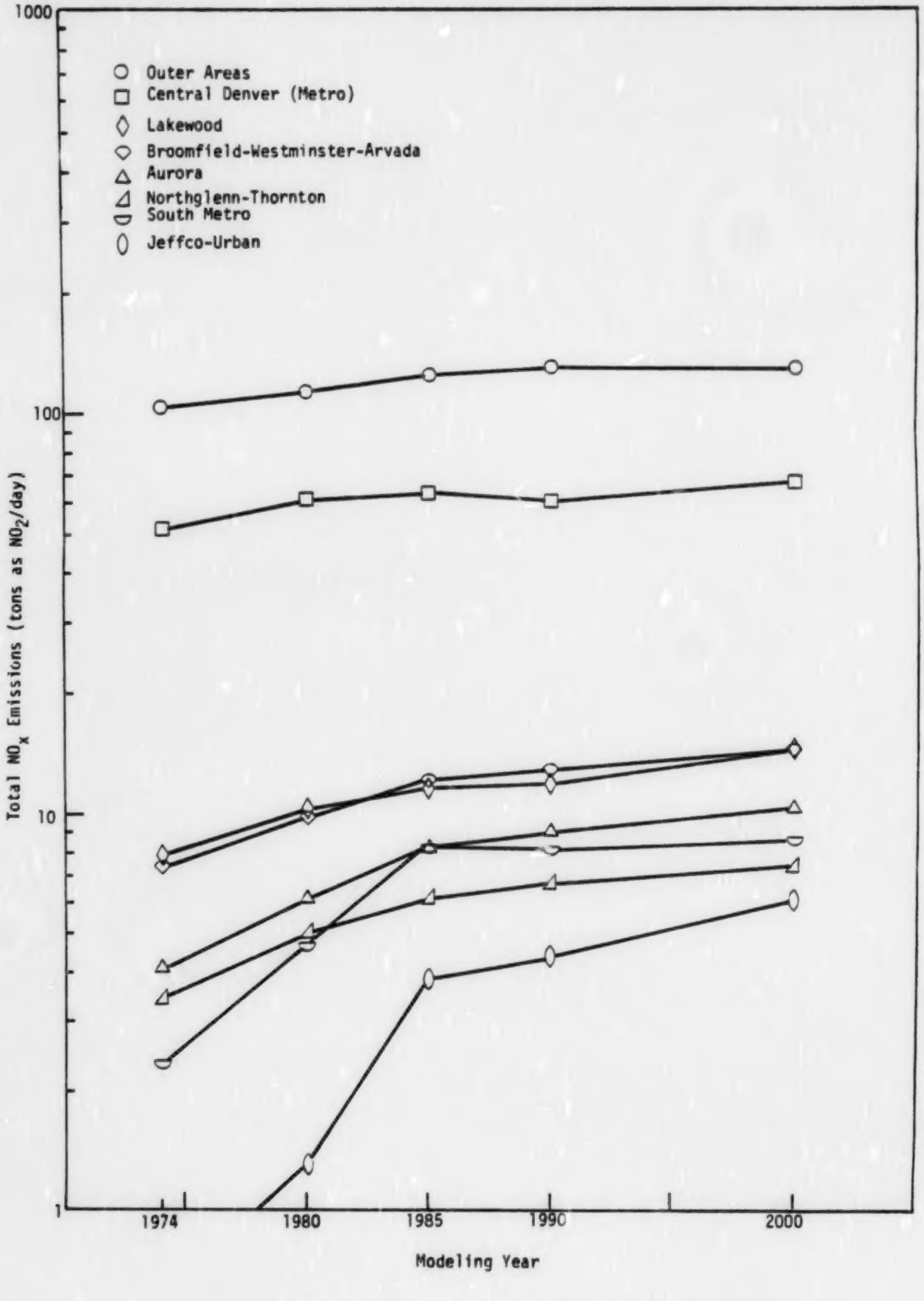

FIGURE B-15. NITROGEN OXIDE EMISSIONS IN SUBREGIONS INPUT TO THE CDM MODEL

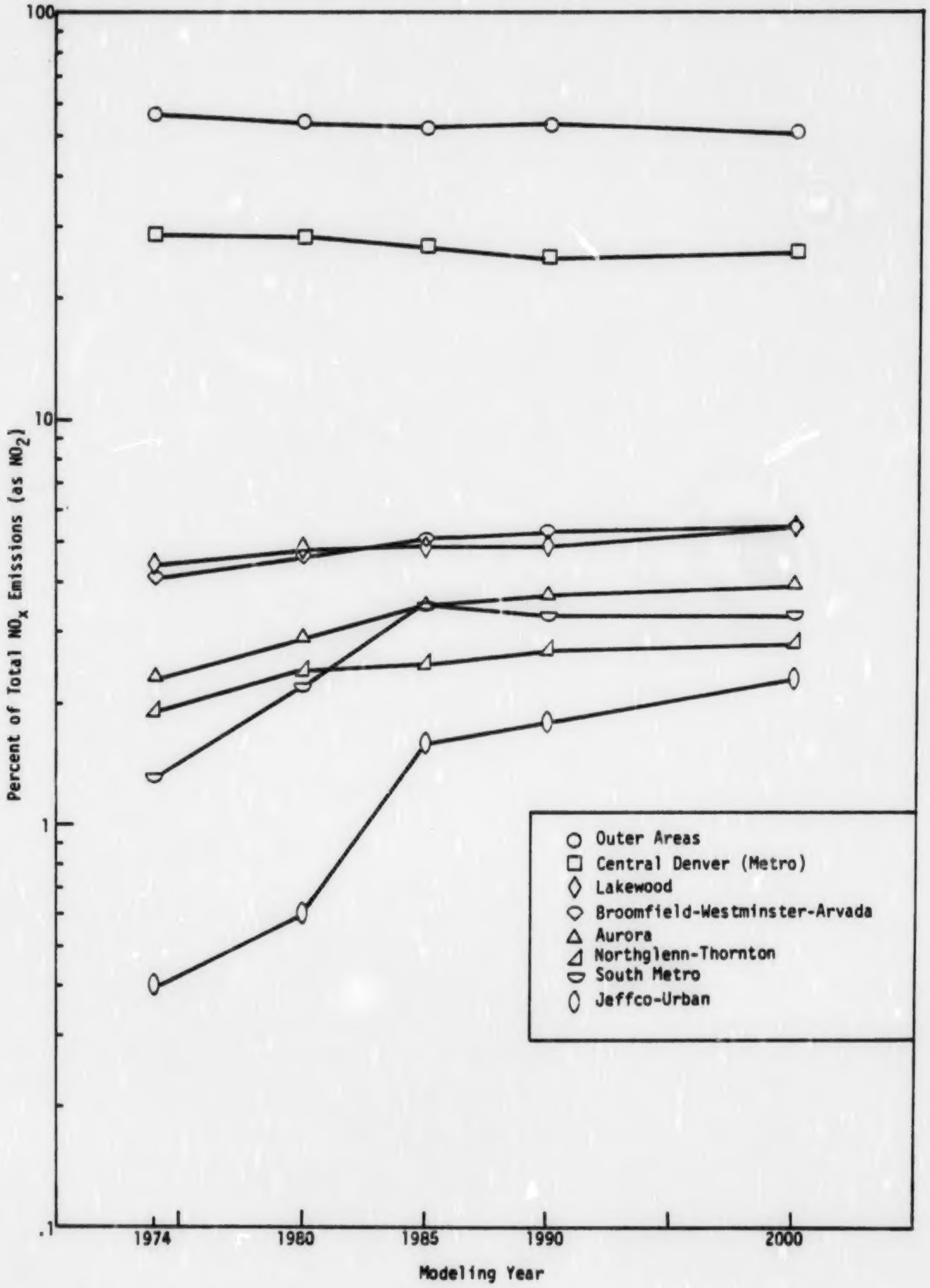

FIGURE B-16. PERCENTAGE CONTRIBUTION OF SUBREGIONS TO NITROGEN OXIDE EMISSIONS

TABLE B-10. SIZE OF THE SUBREGIONS SELECTED FOR SENSITIVITY STUDY

Subregion		Number of Grid Squares*
1	Outer	509
2	Broomfield-Westminster-Arvada	75
3	Northglenn-Thornton	31
4	Aurora	64
5	South Metro	41
6	Jeffco-Urban	27
7	Lakewood	41
8	Central Denver	112

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* Note: each grid unit is one square mile.

TABLE B-11. PARTICULATE EMISSIONS DENSITY BY SUBREGION (kg/day/sq. mi.)

		Year				
	Subregion	1974	1980	1985	1990	2000
1	Outer	64.0	72.8	92.4	101	100
2	Broomfield-Westminster-Arvada	82.4	105	129	144	163
3	Northglen Thornton	91.6	123	147	193	198
4	Aurora	76.8	95.6	120	146	164
5	South Metro	82.8	106	160	198	193
6	Jeffco-Urban	43.6	56	129	323	352
7	Lakewood	162	197	230	300	305
8	Central Denver	270	330	374	410	430
	Average	98	118	144	170	176

TABLE B-12. NITROGEN OXIDE EMISSIONS (AS NO_2) DENSITY BY SUBREGIONS (kg/day/sq. mi.)

Subregion		Year				
		1974	1980	1985	1990	2000
1	Outer	202	226	248	257	259
2	Broomfield-Westminster-Arvada	98.8	130	163	172	193
3	Northglenn-Thornton	110	162	198	214	239
4	Aurora	64.8	96	131	141	161
5	South Metro	58.4	115	205	200	214
6	Jeffco-Urban	23.2	47.6	144	162	227
7	Lakewood	194	249	288	293	351
8	Central Denver	461	544	570	547	610
	Average	200	237	268	272	291

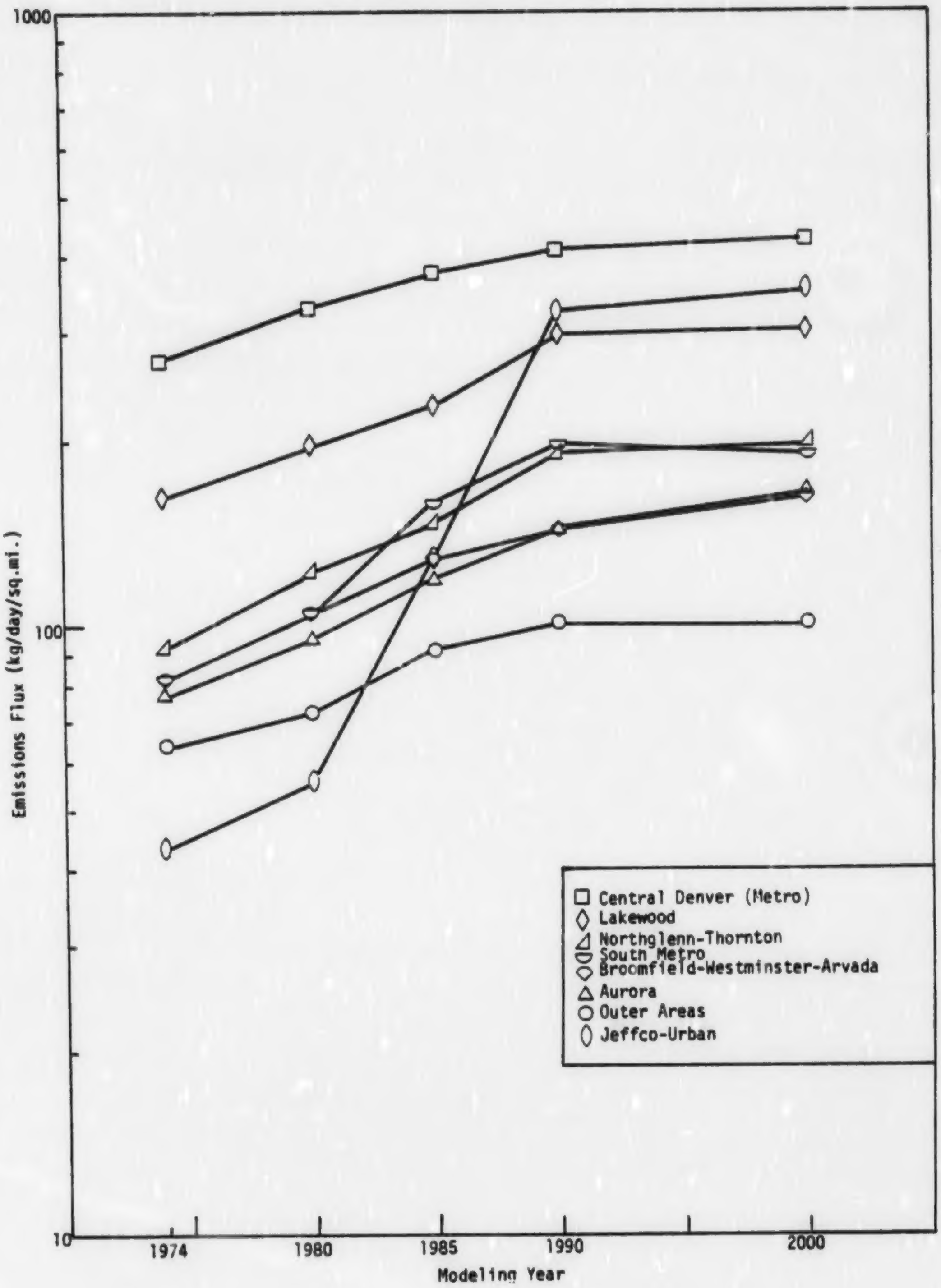

FIGURE B-17. PARTICULATE EMISSIONS FLUX IN THE SUBREGIONS

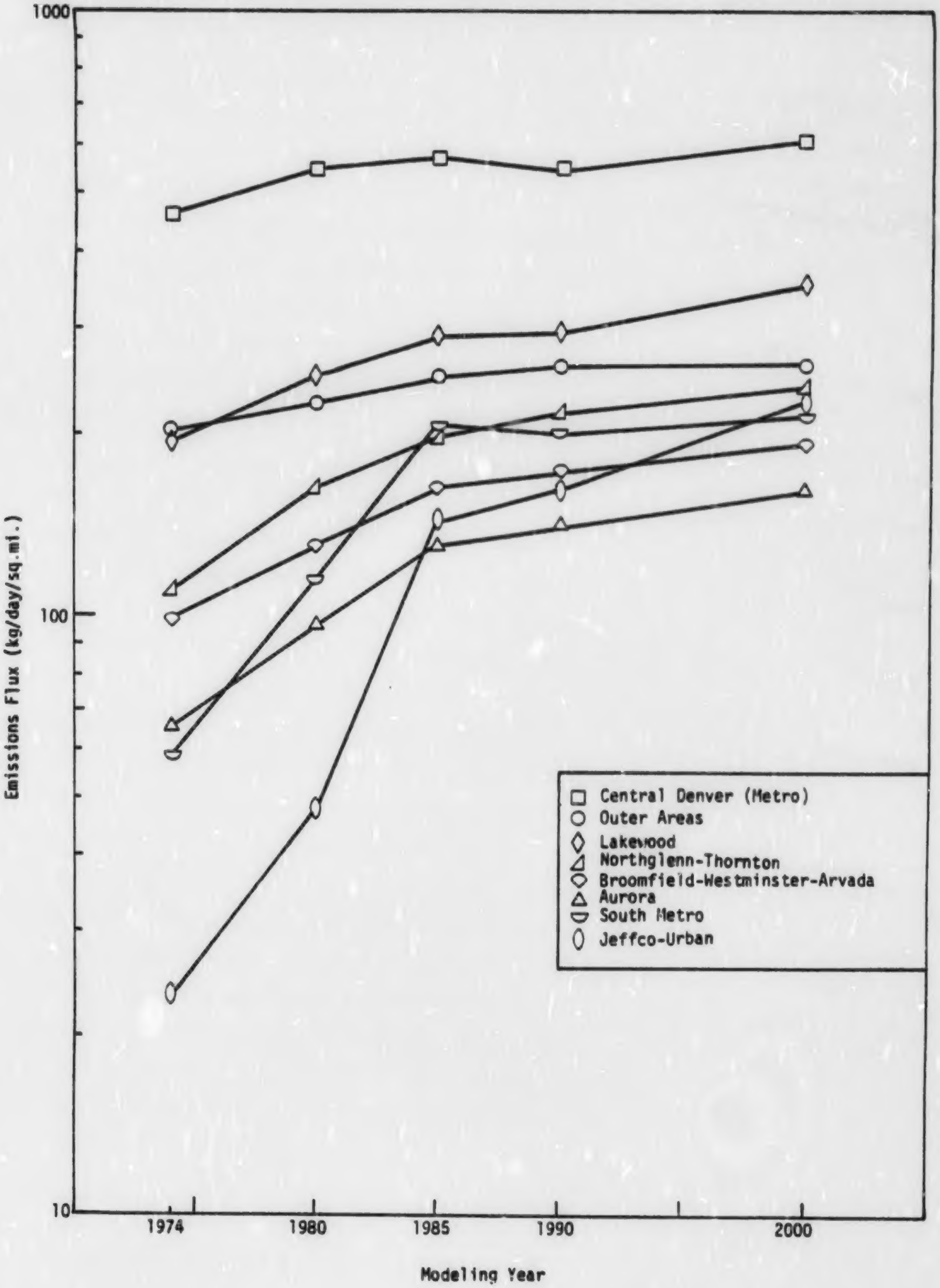

FIGURE B-18. NITROGEN OXIDES EMISSIONS (AS NO_2) IN THE SUBREGIONS requirements differ significantly from the input requirements of CDM. In the first place, the Denver Model requires emissions of reactive hydrocarbons and nitrogen oxides to determine the concentrations of photochemical oxidants. If carbon monoxide concentrations are to be predicted, then CO emissions must also be input. The reactive hydrocarbon emissions are further split into emissions of aldehydes, olefins, aromatics, and paraffins. In the second place, since short-term averages are desired, short-term variations in the emission rates, such as diurnal and seasonal variations, must be accounted for.

The emissions used as inputs to the Denver Model were analyzed by means of a special computer program to determine the contributions arising from each source category. These analyses for the summer and winter months of 1975, 1985, and 2000 are presented in Tables B-13 and B-14, and in Figures B-19 through B-22. An examination of these tables and figures reveals the following:

> Winter emissions exceed summer emissions for reactive hydrocarbons, nitrogen oxides, and carbon monoxide. This is apparently due to an increase in auto emissions and "other area" emissions in the winter. The most significant differences between winter and summer emissions are for carbon monoxide.
> Emissions of carbon monoxide and reactive hydrocarbons decrease in future years, apparently due to a reduction in automobile emissions as a result of the Federal Motor Vehicle Control Program.
> Emissions of nitrogen oxides increase in future years, apparently due to an increase in emissions from automobiles and a few other sources. The fact that total auto emissions increase in spite of the Federal program is probably due to the increasing flow of traffic. "Other area" emissions of nitrogen oxides also appear to rise significantly in future years.
> Automobiles appear to be the prime source of pollution, contributing about 75 percent of the reactive hydrocarbons, 45 percent of the nitrogen oxides, and 85 percent of the carbon monoxide.

TABLE B-13. TOTAL EMISSIONS INPUTS TO THE DENVER MODEL--SUMMER. A = tons per day, B = percent of total.

(a) Year 1975

	RHC		URHC		NO		NO_2		Total NO_x as NO_2		CO	
	A	B	A	B	A	B	A	B	A	B	A	B
Airport	4.30	2.4%	1.07	1.8%	2.27	1.9%	0.39	1.6 %	3.87	1.8%	21.1	1.1%
Auto area	1.35	0.74	0.34	0.57	0.23	0.2	0.039	0.16	0.39	0.18	17.9	0.91
Auto link	148.1	81.4	49.9	84.0	49.1	40.0	8.30	34.3	83.6	39.4	1730	88.0
Subtotal	153.7	84.5	51.3	86.4	51.6	42.1	8.72	36.0	87.8	41.4	1769	90.0
Other area	1.90	1.0	0.48	0.81	3.16	2.6	0.54	2.2	5.4	2.5	1.93	0.098
Small point sources	13.1	7.2	3.28	5.5	1.38	1.1	0.23	1.0	2.35	1.1	2.56	0.13
Subtotal	168.8	92.7	55.0	92.6	56.1	45.7	9.50	39.3	95.5	45.0	1774	90.3
Large point sources*	13.2	7.3	4.4	7.4	66.6	54.3	14.7	60.7	116.8	55.0	190.9	9.9
Total	182.0	100	59.4	100	122.7	100	24.2	100	212.3	100	1965	100

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*Hydrocarbon emissions from large point sources are assumed to be 75 percent reactive hydrocarbons (RHC) and 25 percent unreactive hydrocarbons (URHC).

TABLE B-14 (Continued)

(b) Year 1985

	RHC		URHC		NO		NO_2		Total NO_x as NO_2		CO	
	A	B	A	B	A	B	A	B	A	B	A	B
Airport	5.28	3.8%	1.32	2.9%	3.08	2.0%	0.52	1.7%	5.24	2.0%	25.2	1.7%
Auto area	0.56	0.41	0.14	0.31	0.84	0.5	0.14	0.5	1.43	0.53	8.71	0.58
Auto link	106.7	77.2	36.8	80.3	71.4	45.9	12.1	40.6	121.6	45.3	1278	84.7
Subtotal	112.6	81.4	38.3	83.6	75.3	48.4	12.8	43.0	128.3	47.8	1312	87.0
Other area	0.43	0.31	0.108	0.24	4.03	2.6	0.69	2.3	6.9	2.5	1.35	0.09
Small point sources	12.0	8.7	3.01	6.6	9.68	6.2	1.65	5.5	16.5	6.1	3.88	0.26
Subtotal	125.0	90.4	41.4	90.4	89.1	57.2	15.1	50.7	151.7	56.5	1317	87.3
Large point sources*	13.2	9.6	4.4	9.6	66.6	42.8	14.7	49.3	116.8	43.5	190.9	12.7
Total	138.2	100	45.8	100	155.7	100	29.8	100	268.5	100	1508	100

TABLE B-14 (Concluded)

(c) Year 2000

	RHC		URHC		NO		NO_2		Total NO_x as NO_2		CO	
	A	B	A	B	A	B	A	B	A	B	A	B
Airport	5.28	5.0%	1.32	4.0%	3.08	1.9%	0.52	1.7%	5.24	1.9%	25.2	2.3%
Auto area	0.21	0.20	0.053	0.16	0.14	0.1	0.024	0.1	0.24	0.087	3.47	0.32
Auto link	73.6	69.9	24.3	72.8	71.2	44.3	12.1	39.4	121.3	43.8	866.2	79.2
Subtotal	79.1	75.1	25.7	76.9	74.4	46.3	12.7	41.4	126.8	45.8	894.9	81.9
Other area	0.986	0.94	0.247	0.74	9.91	6.2	1.69	5.5	16.9	6.1	3.08	0.28
Small point sources	12.0	11.4	3.01	9.0	9.68	6.0	1.65	5.4	16.5	6.0	3.88	0.35
Subtotal	92.1	87.5	29.0	86.8	94.0	58.5	16.0	52.1	160.1	57.8	901.8	82.5
Large point sources*	13.2	12.5	4.4	13.2	66.6	41.5	14.7	47.9	116.8	42.2	190.9	17.5
Total	105.3	100	33.4	100	160.6	100	30.7	100	276.9	100	1093	100

# TABLE B-14. TOTAL EMISSIONS INPUTS TO THE DENVER MODEL--WINTER.
A = tons per day, B = percent of total.

(a) Year 1974

	RHC		URHC		NO		NO_2		Total NO_x as NO_2		CO	
	A	B	A	B	A	B	A	B	A	B	A	B
Airport	4.30	1.8%	1.07	1.3%	2.27	1.7%	0.39	1.5%	3.87	1.7%	21.1	0.69%
Auto area	1.93	0.79	0.48	0.60	0.33	0.2	0.056	0.2	0.56	0.24	25.5	0.83
Auto link	206.8	84.2	69.5	86.7	53.9	40.0	9.19	34.9	91.8	39.4	2793	91.9
Subtotal	213.0	86.8	71.0	88.5	56.5	41.9	9.63	36.6	96.3	41.4	2840	93.4
Other area	6.18	2.5	1.55	1.9	10.3	7.6	1.75	6.7	17.5	7.5	6.28	0.21
Small point sources	13.1	5.3	3.28	4.1	1.35	1.0	0.23	0.9	2.3	1.0	2.56	0.084
Subtotal	232.3	94.6	75.8	94.5	68.1	50.6	11.6	44.1	116.0	49.8	2849	93.7
Large point sources*	13.2	5.4	4.4	5.5	66.6	49.4	14.7	55.9	116.8	50.2	190.9	6.3
Total	245.5	100	80.2	100	134.7	100	26.3	100	232.8	100	3040	100

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* Large point hydrocarbon emissions are assumed to be 75 percent RHC and 25 percent URHC.

TABLE B-14 (Continued)

(b) Year 1985

	RHC		URHC		NO		NO_2		Total NO_x as NO_2		CO	
	A	B	A	B	A	B*	A	B*	A	B*	A	B
Airport	5.28	3.1%	1.32	2.4%	3.08		0.52		5.24		25.2	1.1%
Auto area	0.75	0.44	0.19	0.34	0.92		0.16		1.57		14.6	0.64
Auto link	138.4	80.9	46.5	83.3	--*		--*		--*		2034	89.5
Subtotal	144.4	84.4	48.0	86.0	--*		--*		--*		2074	91.2
Other area	1.4	0.82	0.35	0.63	13.1		2.23		22.3		4.38	0.19
Small point sources	12.0	7.0	3.01	5.4	9.63		1.65		16.5		3.88	0.17
Subtotal	157.9	92.3	51.4	92.1	--*		--*		--*		2082	91.6
Large point sources†	13.2	7.7	4.4	7.9	66.6		14.7		116.8		190.9	8.4
Total	171.1	100	55.8	100	--*		--*		--*		2273	100

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* The emissions factors used as inputs to compute auto link NO_x emissions were in error.

† Large point hydrocarbon emissions are assumed to be 75 percent RHC and 25 percent URHC.

TABLE B-14 (Concluded)

(c) Year 2000

	RHC		URHC		NO		NO_2		Total NO_x as NO_2		CO	
	A	B	A	B	A	B	A	B	A	B	A	B
Airport	5.28	4.5%	1.32	3.5%	3.08	1.6%	0.52	1.5%	5.24	1.6%	25.2	2.1%
Auto area	0.38	0.33	0.095	0.25	0.23	0.1	0.040	0.1	0.39	0.12	6.1	0.5
Auto link*	82.7	70.8	28.4	74.7	79.9	41.7	13.4	37.4	135.9	41.2	983.4	80.6
Subtotal	88.4	75.7	29.5	78.4	83.2	43.4	14.0	39.1	141.6	42.9	1015	83.2
Other area	3.2	2.7	0.80	2.1	32.2	16.8	5.48	15.3	54.9	16.7	10.0	0.82
Small point sources	12.0	10.3	3.0	7.9	9.7	5.1	1.6	4.5	16.5	5.0	3.9	0.32
Subtotal	103.6	88.7	33.6	88.4	125.1	65.3	21.1	58.9	212.9	64.6	1029	84.3
Large point sources†	13.2	11.3	4.4	11.6	66.6	34.7	14.7	41.1	116.8	35.4	190.9	15.6
Total	116.8	100	38.0	100	191.7	100	35.8	100	329.7	100	1220	99.9

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* The emissions factors used to compute auto link emissions were in error.

† Large point emissions are assumed to be 75 percent RHC and 25 percent URHC.

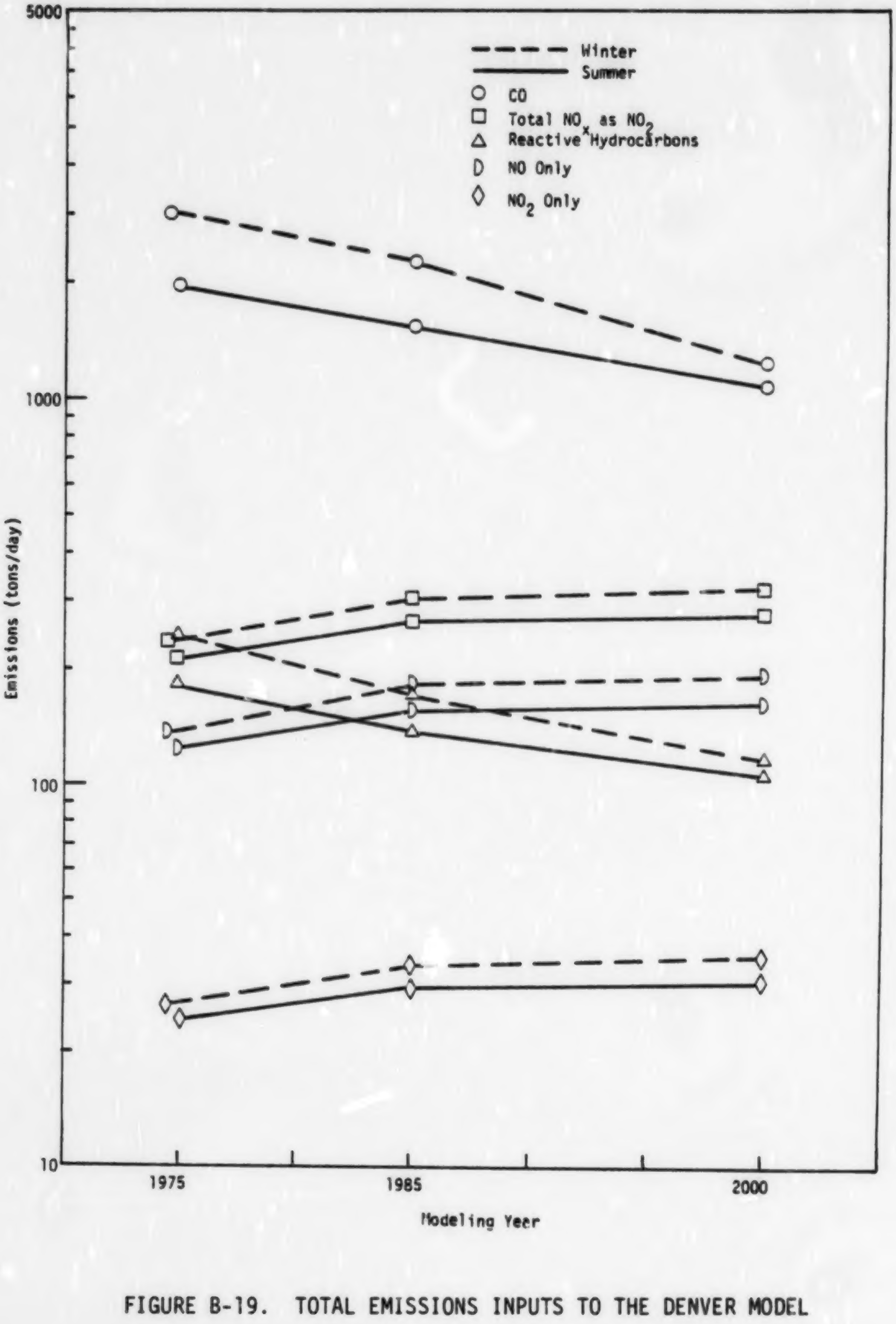


FIGURE B-19. TOTAL EMISSIONS INPUTS TO THE DENVER MODEL

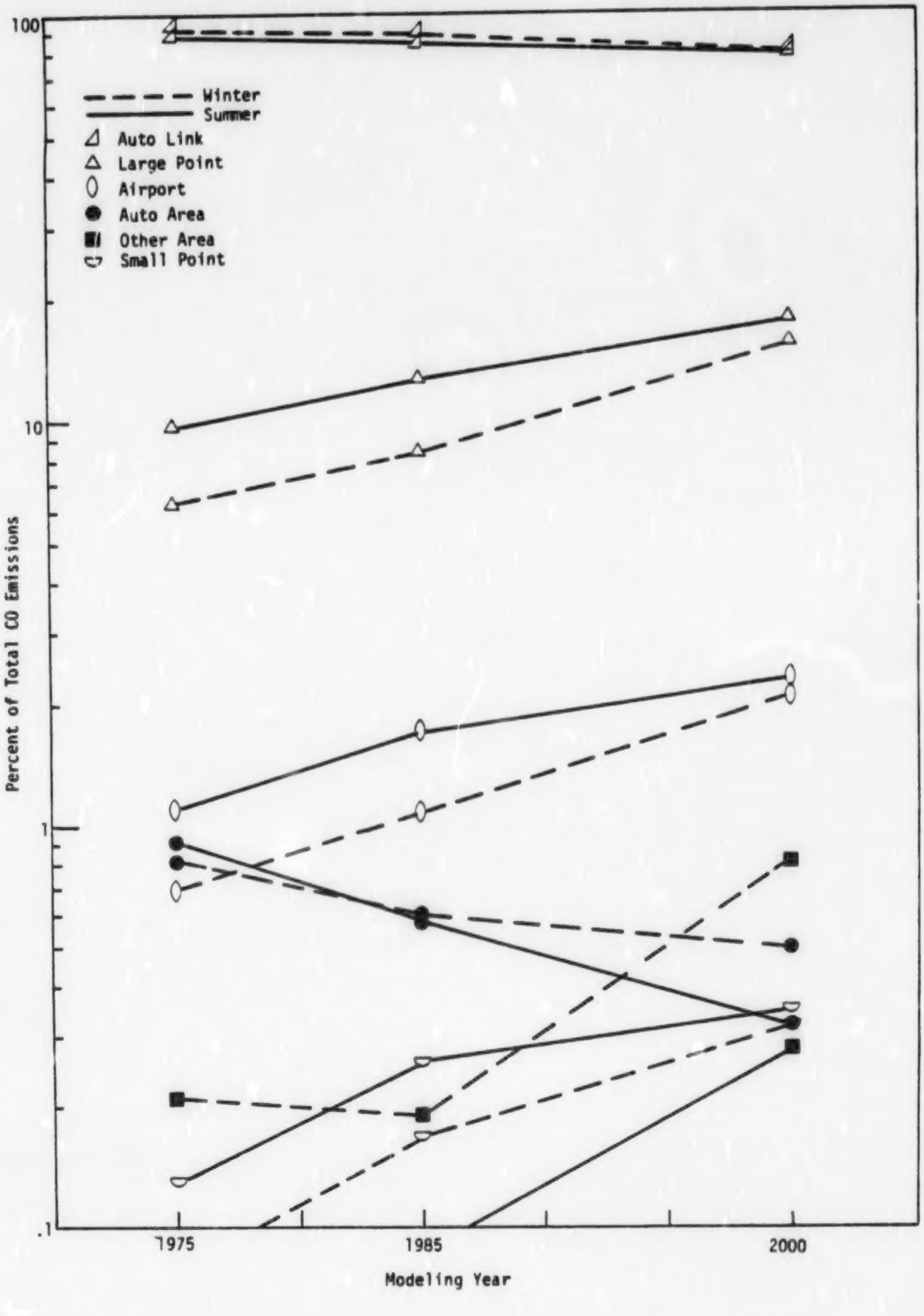


FIGURE B-20. PERCENTAGE CONTRIBUTION OF SOURCE CATEGORIES TO CARBON MONOXIDE EMISSIONS

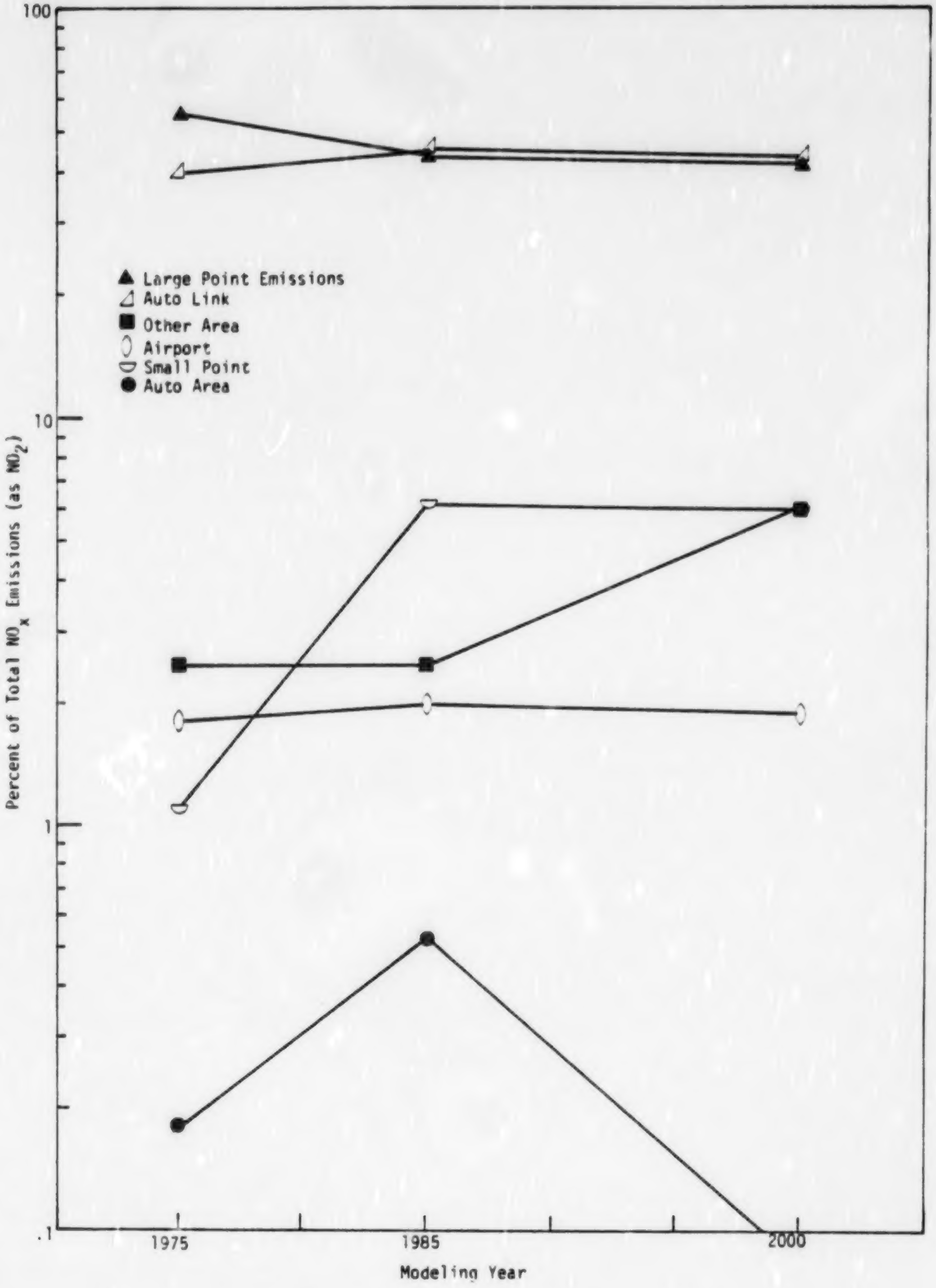


FIGURE B-21. PERCENTAGE CONTRIBUTION OF SOURCE CATEGORIES TO NITROGEN OXIDE EMISSIONS--SUMMER

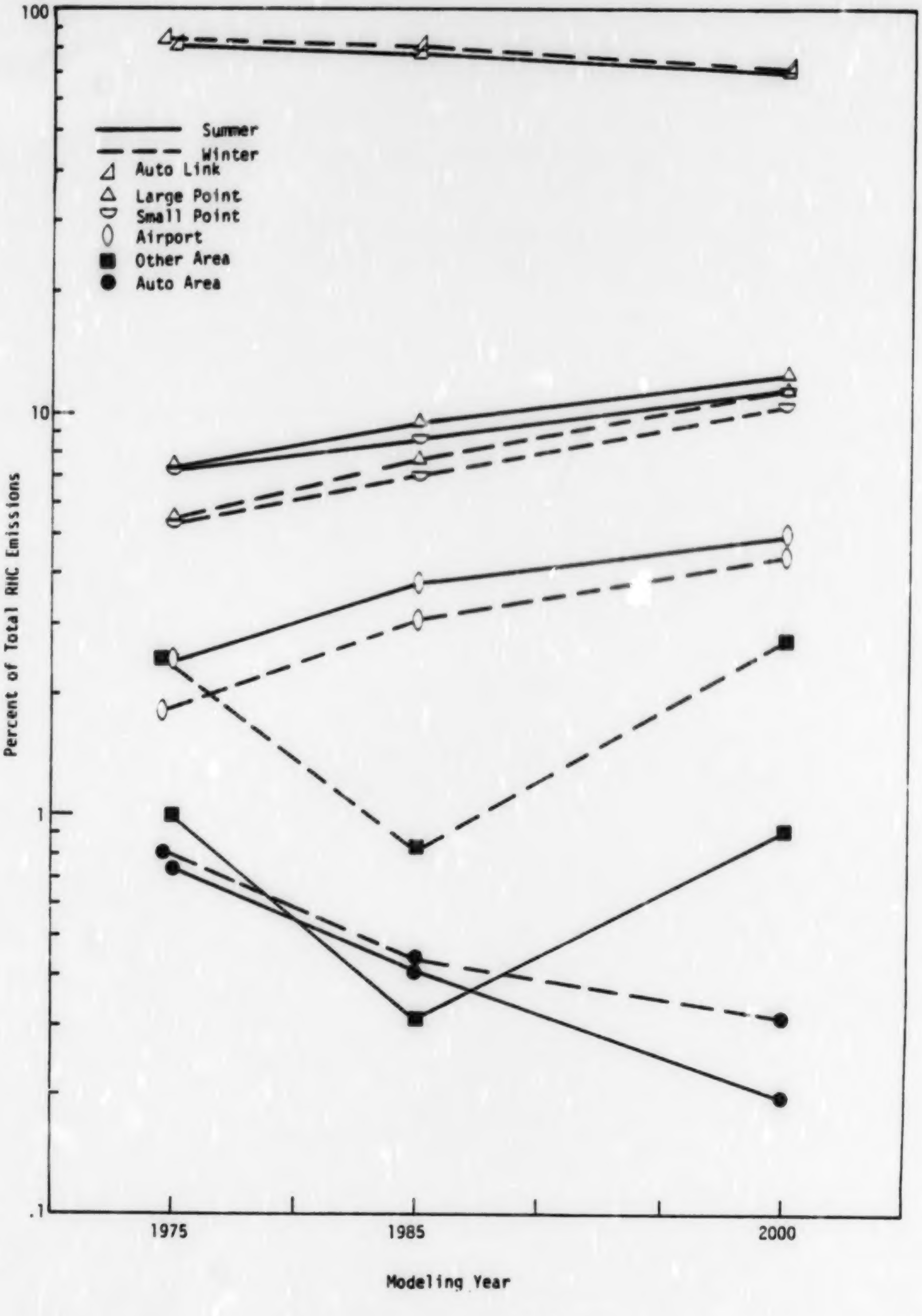


FIGURE B-22. PERCENTAGE CONTRIBUTION OF SOURCE CATEGORIES TO REACTIVE HYDROCARBON EMISSIONS

> Point sources are the second largest source of pollutants, contributing about 20 percent of the reactive hydrocarbons, 50 percent of the nitrogen oxides, and 10 percent of the carbon monoxide.

As in the case of CDM emissions inputs, the Denver Model emissions inputs were analyzed to determine the total emissions from each of the subregions delineated for the sensitivity study. These results are presented in Table B-15 and Figures B-23 through B-28. Central Denver has by far the largest emissions of the seven regions chosen for study. The "outer" area not included in the sensitivity study accounts for a suprisingly large portion of the total emissions, especially for the oxides of nitrogen (over 55 percent). The emissions in some of the southern subregions such as South Metro and Jeffco-Urban either do not decrease as rapidly as the emissions in the other regions in the cases of reactive hydrocarbons and carbon monoxide or increase relatively rapidly (in the case of nitrogen oxides). However, these subregions still only contribute a few percent of the total pollutant loading for the entire modeling region.

TABLE B-15. EMISSIONS IN SUBREGIONS AS INPUT TO THE DENVER MODEL--SUMMER. A = tons per day, B = percent of total.

	1975						1985						2000					
	RHC		NO_x as NO_2		CO		RHC		NO_x as NO_2		CO		RHC		NO_x as NO_2		CO	
Subregion	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1 Outer	47.5	26.1%	132.5	62.4%	577.9	29.4%	41.9	30.3%	154.2	57.4%	519	34.4%	31.5	29.9%	154.5	55.8%	395.4	36.2
2 Broomfield-Westminster-Arvada	11.9	6.5	7.06	3.3	128.2	6.5	9.72	7.0	11.7	4.4	109	7.2	7.02	6.7	12.7	4.6	74.8	6.8
3 Northglenn-Thornton	5.15	2.8	3.15	1.5	53.1	2.7	4.22	3.1	5.66	2.1	44.3	2.9	3.23	3.1	6.27	2.3	32.4	3.0
4 Aurora	9.73	5.3	4.20	2.0	85.1	4.3	8.76	6.3	8.08	3.0	81.2	5.4	7.19	6.8	8.78	3.2	62.3	5.7
5 South Metro	4.78	2.6	2.39	1.1	51.3	2.6	5.75	4.2	8.43	3.1	63.7	4.2	4.04	3.8	8.48	3.1	42.1	3.9
6 Jeffco-Urban	0.984	0.54	0.674	0.32	10.9	0.55	3.32	2.4	4.04	1.5	42.0	2.8	2.61	2.5	5.16	1.9	30.2	2.8
7 Lakewood	13.3	7.3	7.72	3.6	144.1	7.3	9.21	6.7	11.42	4.3	100.5	6.7	7.15	6.8	13.59	4.9	71.1	6.5
8 Central Denver	88.7	48.7	54.6	25.7	913.8	46.5	55.4	40.1	64.9	24.2	548.6	36.4	42.6	40.4	67.45	34.4	384.3	35.2
Total	182.1	99.8	212.3	99.9	1964.4	99.9	138.3	100.1	268.5	100	1508	100	105.4	100	276.9	100.2	1093	100.1

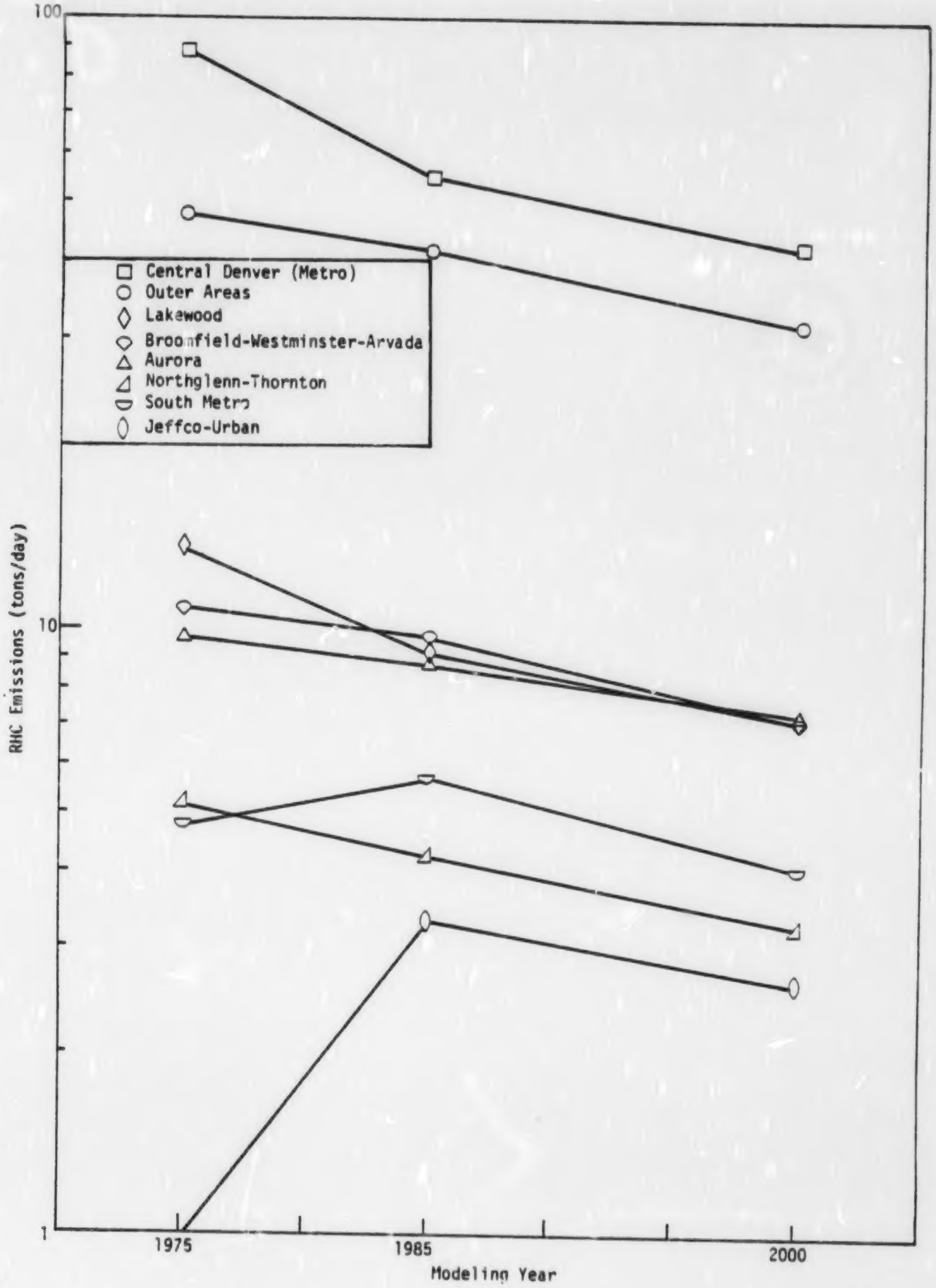


FIGURE B-23. REACTIVE HYDROCARBON EMISSIONS IN SUBREGIONS--SUMMER

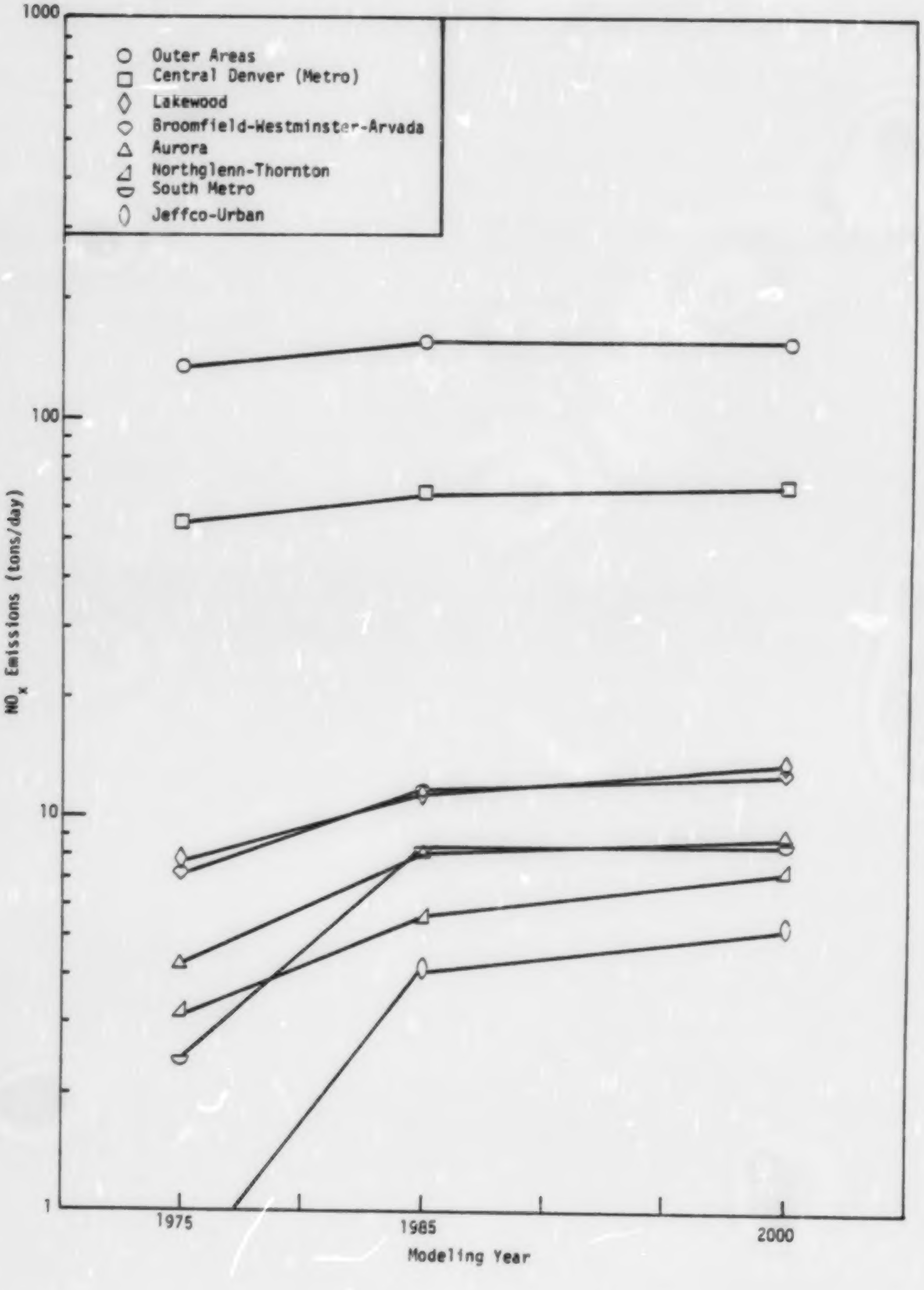


FIGURE B-24. NITROGEN OXIDE EMISSIONS IN SUBREGIONS--SUMMER

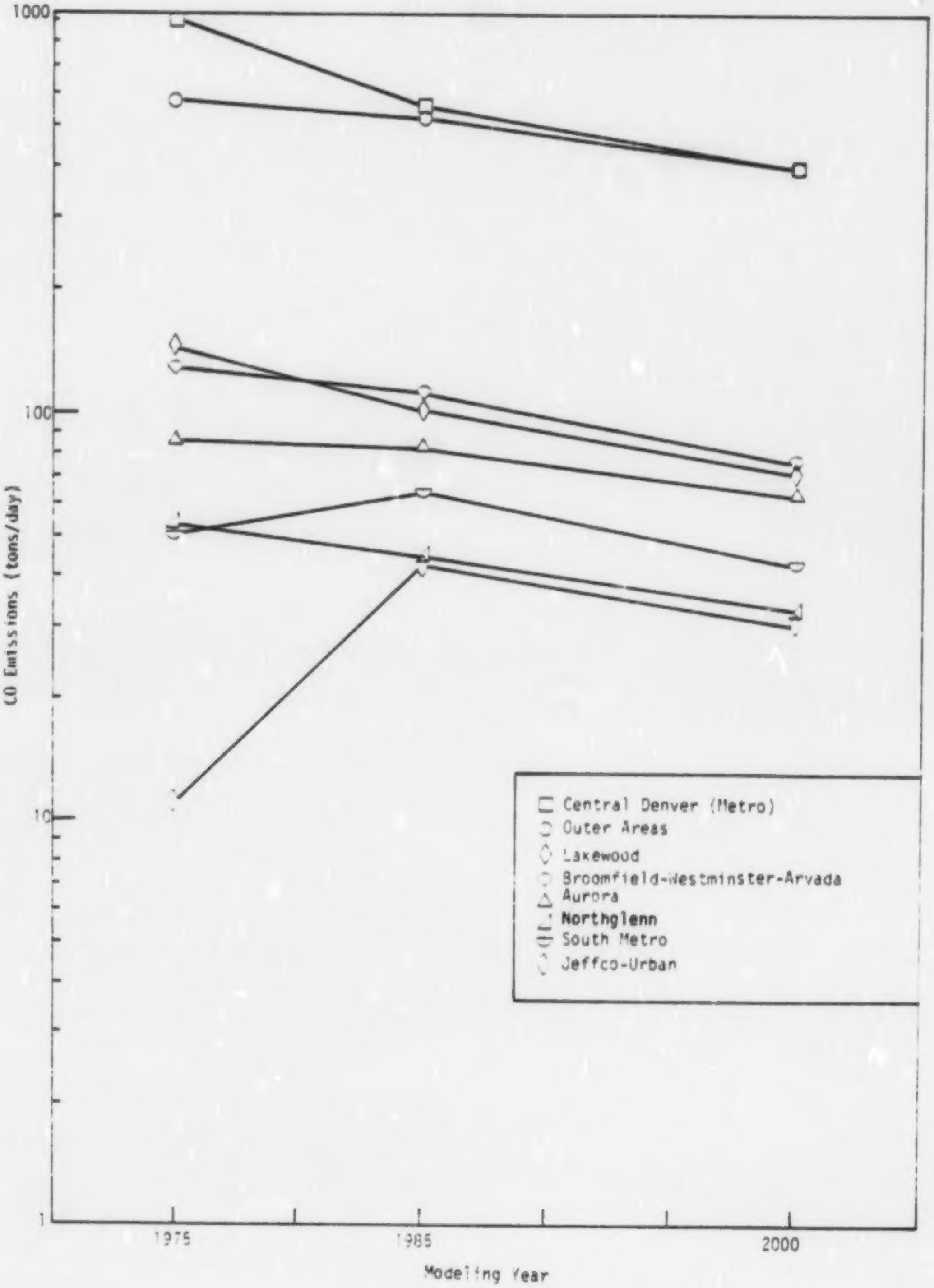


FIGURE B-25. CARBON MONOXIDE EMISSIONS IN SUBREGIONS--SUMMER

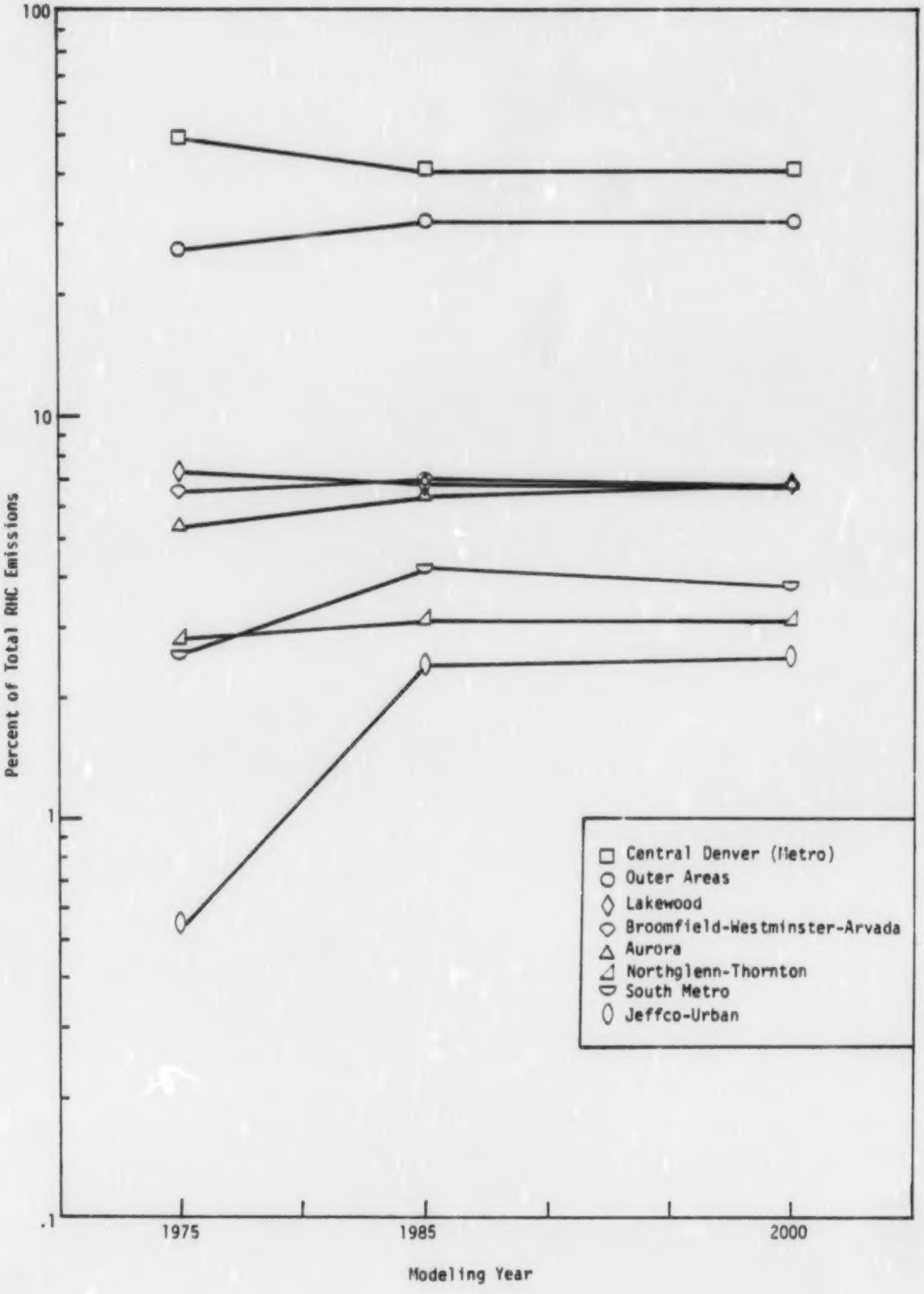


FIGURE B-26. PERCENTAGE CONTRIBUTION OF SUBREGIONS TO REACTIVE HYDROCARBON EMISSIONS--SUMMER

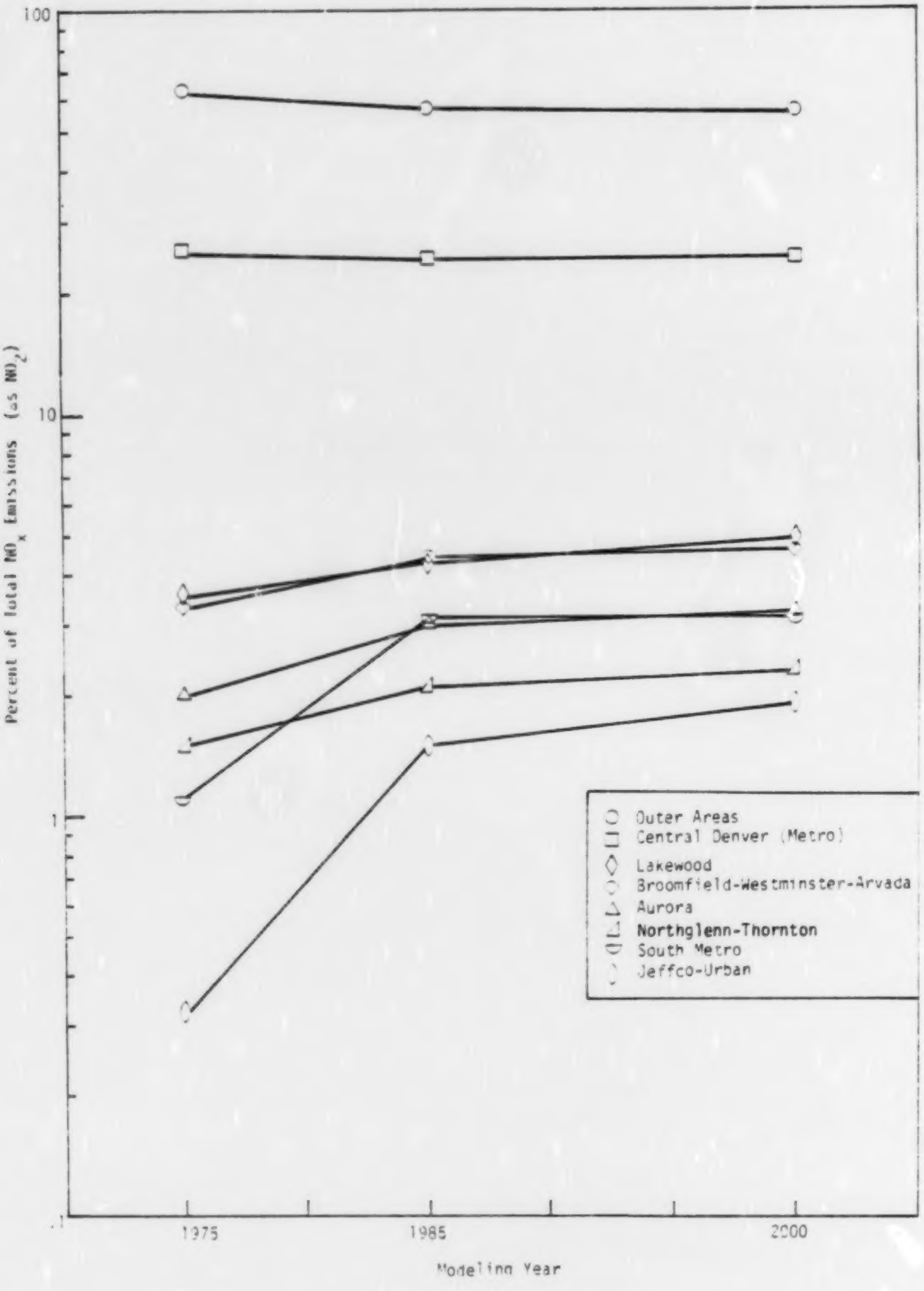


FIGURE B-27. PERCENTAGE CONTRIBUTION OF SUBREGIONS TO NITROGEN OXIDE EMISSIONS--SUMMER

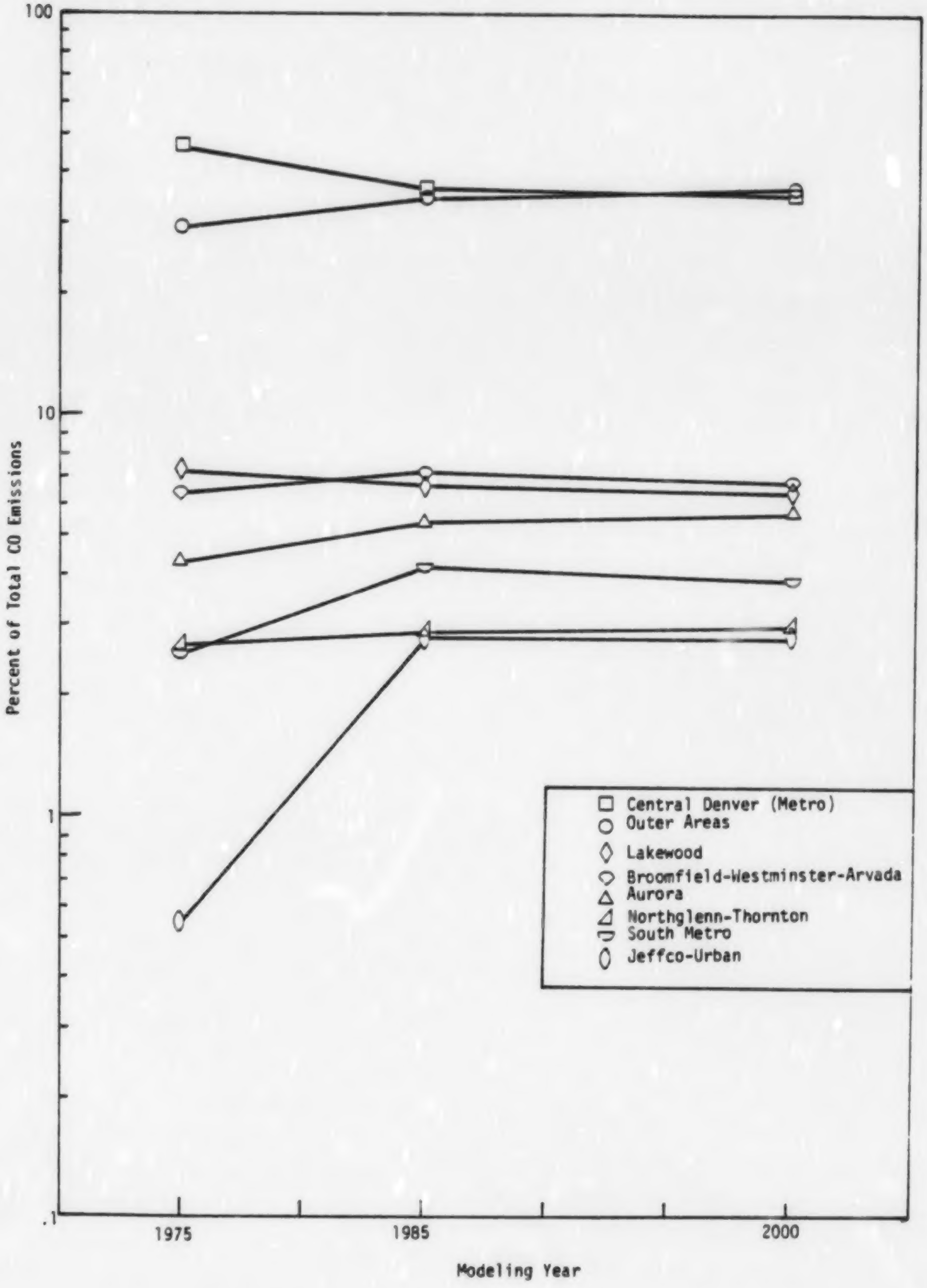


FIGURE B-28. PERCENTAGE CONTRIBUTIONS OF SUBREGIONS TO CARBON MONOXIDE EMISSIONS--SUMMER

APPENDIX C

DENVER REGIONAL PLANNING OVERVIEW (AS OF 24 NOVEMBER 1976)

AUTHOR'S NOTE

The reliability of an airshed model simulation is heavily dependent on the quality and consistency of the data supplied to it. Because several agencies separately provided SAI with portions of the data we used, and because different data vintages existed within each agency, it became essential early in the Overview EIS project to develop a full perspective on the Denver planning process. This was particularly necessary for those planning aspects having direct impact on air quality: population level and allocation, land use, and transportation.

This appendix was completed in November 1976, early enough to provide SAI with the perspective needed to guide its analysis efforts. We believe its portrayal of Denver regional planning is accurate as of its publication date. Subsequent events, however, are not reflected in the text. We urge the reader to consider this fact when evaluating its contents.

The most significant change occurring since publication concerns the role of the Denver Regional Council of Governments (DRCOG). This appendix refers to the Joint Regional Planning Program (JRPP) as the designated Metropolitan Planning Organization (MPO), with the DRCOG serving as the policy body of the JRPP. That relationship has since been altered. As a result of a three-party agreement between the DRCOG, the Regional Transportation District (RTD) and the Colorado Division of Highways (CDH)--an accord officially sanctioned by the Governor--the DRCOG has now been designated as the MPO in the Denver region. In this new role DRCOG supplants the JRPP. Both the RTD and the CDH, previously members of the JRPP, are now no longer a part of the MPO.

APPENDIX C

DENVER REGIONAL PLANNING OVERVIEW (AS OF 24 NOVEMBER 1976)

by Stanley R. Hayes

1. INTRODUCTION

a. Task Objective

Systems Applications, Incorporated, under contract to the Environmental Protection Agency, Region VIII, is preparing the air quality element for the Denver Metropolitan Wastewater Facilities Overview EIS.

The broad geographical scope of this study emphasizes the importance of comprehensive regional planning. To address regional issues while balancing contending local interests, any such process must be a dynamic one. Sensitivity and responsiveness require continual improvement and reexamination. As a result, planning must be viewed as evolutionary.

The analysis of primary and secondary air quality impacts, however, is acutely sensitive to the assumptions imbedded in regional plans. As an area characterized by extensive ownership and usage of private automobiles, Metropolitan Denver is particularly subject to elevated levels of carbon monoxide (CO) and hydrocarbons (HC). The distribution and intensity of the resulting automobile-produced mixture is strongly dependent on population, land use, and the transportation network. To the extent that uncertainties exist in any of these areas, air quality must likewise be considered in question. These issues are further complicated by the nonlinear relationship of pollutant concentrations to vehicle-miles-traveled (VMT).

In order to perform properly the analysis required by the Overview EIS, SAI must consider all those uncertainties having a direct bearing on air quality. SAI has no intention of intruding on the planning process or of considering planning alternatives other than those that have already been the subject of analyses by agencies within the Denver region.

Guided by the above caveat it is the purpose of this task report to consider the planning process in the Denver Metropolitan region, as to both institutional framework and substantive policy issues. The role of specific agencies will be explored, along with their particular perspectives on population, land use and transportation network alternatives.

Because the analyses to be performed by SAI will be so heavily driven by the assumptions underlying the input data supplied to it and because several permutations of that data exist within the agencies providing it, a precise, detailed examination of the relevant planning issues is an essential preliminary to the study process.

The results of this task report will be drawn upon heavily in structuring SAI's analysis efforts. Specifically, a base case regional development scenario must be identified along with a complete catalog of the important uncertainties associated with it. A carefully constructed sensitivity analysis must then be conducted to examine the air quality effects of as broad a range of these uncertainties as possible. This report, through its examination in some depth of the critical elements of regional planning, will assure the broadest perspective in SAI's efforts.

b. Report Organization

This report has been partitioned into three broad areas: organizational perspectives, planning issues, and final observations. The first of these, in Section 2, will examine the role in the planning process played by the Joint Regional Planning Program (JRPP), the Denver Regional Council of Governments (DRCOG), the Colorado Division of Highways (CHD), the Regional Transportation District (RTD), and the Air Pollution Control Division of the Colorado Department of Health.

The second area of discussion, an overview of planning issues, will be presented in Section 3. Those issues having the most direct bearing on SAI's air quality modeling will be explored in detail. Both the nature of the issues themselves and their institutionally endorsed variants will be considered.

Finally, in Section 4, planning options considered by the various regional and state agencies mentioned above will be summarized. The impacts of any potential planning uncertainties on the air quality study performed by SAI will be assessed and preliminary recommendations stated.

The references for this appendix are listed at its end.

2. ORGANIZATIONAL PERSPECTIVES

a. Institutional Overview

Since it is the transportation process that exacts so noticeable a price on air quality in the Denver metropolitan area, this institutional overview will concentrate on agencies having direct planning responsibilities in areas bearing most heavily on transportation. These areas include population level and its allocation, land use, transportation planning (highways and rapid transit), and transportation modeling.

1) Air Quality Regulations

A brief historical perspective is helpful at this point. In 1970 the Congress enacted certain amendments to the Clean Air Act (42 U.S.C. 1857). In addition to creating the Environmental Protection Agency (EPA), the Act in Section 110 mandated the preparation and approval of State Implementation Plans (SIP). It was required of each SIP that it set forth specific plans for the attainment and maintenance of the National Ambient Air Quality Standards (NAAQS) to be promulgated by the EPA as part of its statutory responsibilities under Section 109.

For the purposes of air quality evaluation the Administrator of the EPA was empowered by Section 108 of the Clean Air Act to designate boundaries for interstate or intrastate regions called Air Quality Control Regions (AQCR). The State of Colorado was divided into eight regions, as shown in Figure C-1, from Reference 1.

In 1972 AQCRs were classified Priority I or Priority III for the transportation-related pollutants, carbon monoxide (CO), photochemical oxidants (O_x), and nitrogen dioxide (NO_2). These classifications were based on existing air quality measurements, if available, or urban population size, if suitable measurement data were unavailable. The purpose

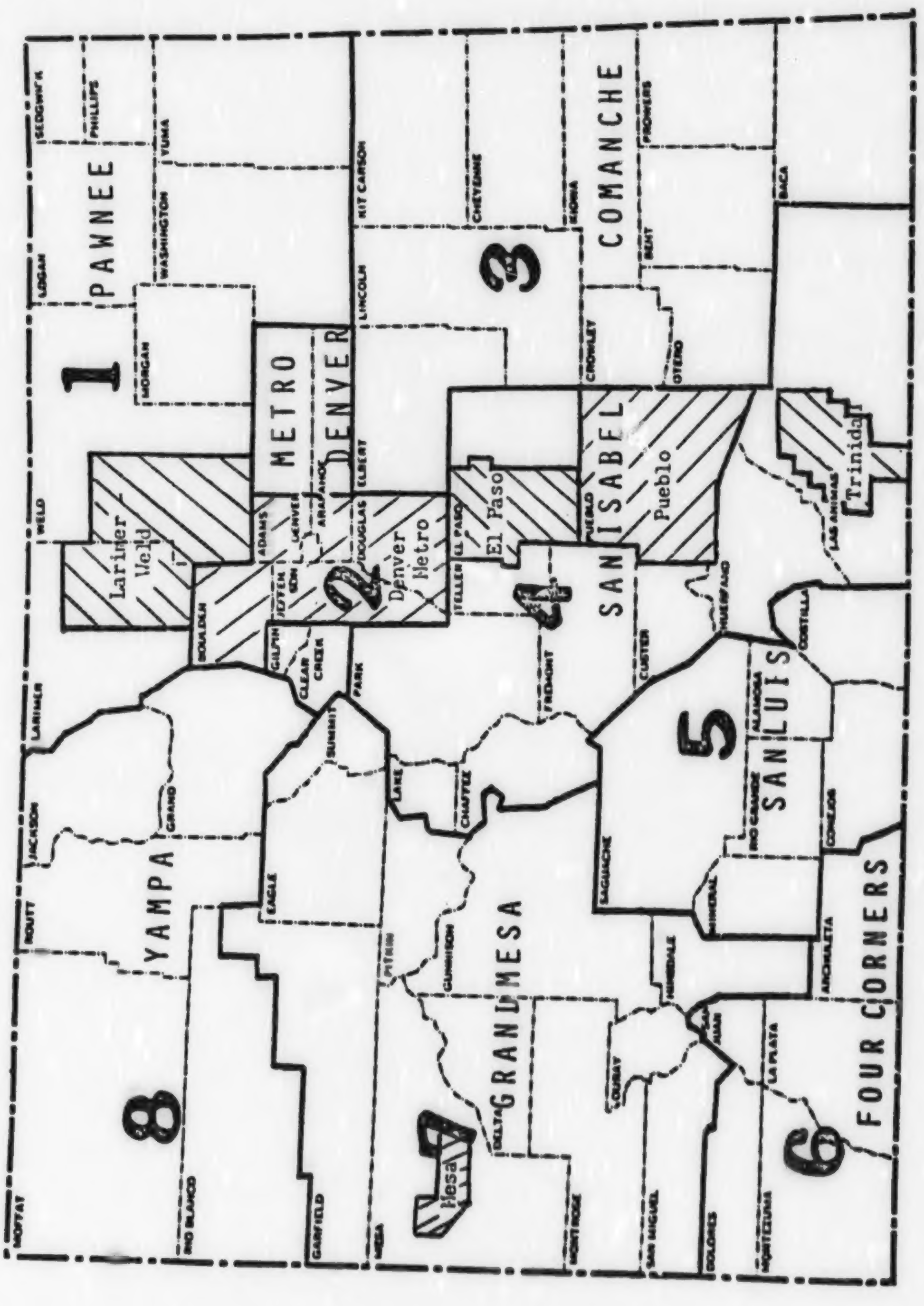

1
PAWNEE
SEDGWICK
PHILLIPS
LOGAN
YUMA
WASHINGTON
MORGAN
WELD
METRO DENVER
Larimer Weld
2
Denver Metro
ADAMS
DENVER
ARAPAHOE
DOUGLAS
JEFFER SON
BOULDER
GILPIN
CLEAR CREEK
PARK
ELBERT
3
COMANCHE
KIT CARSON
LINCOLN
CHEYENNE
KIOWA
PROWERS
BENT
CROWLEY
OTERO
BACA
4
SAN ISABEL
El Paso
Pueblo
Trinidad
EL PASO
TELLER
FREMONT
PUEBLO
CUSTER
HUERFANO
LAS ANIMAS
COSTILLA
5
SAN LUIS
ALAMOSA
RIO GRANDE
CONEJOS
SAGUACHE
MINERAL
6
FOUR CORNERS
ARCHULETA
LA PLATA
SAN JUAN
MONTEZUMA
DOLORES
7
GRAND MESA
Mesa
MESA
DELTA
MONTROSE
OURAY
SAN MIGUEL
HINSDALE
GUNNISON
PITKIN
8
YAMPA
MOFFAT
RIO BLANCO
GARFIELD
ROUTT
JACKSON
GRAND
EAGLE
SUMMIT
LAKE
CHAFFEE
LARIMER

FIGURE C-1. COLORADO AIR QUALITY CONTROL REGIONS AND STATE AIR POLLUTION CONTROL DESIGNATED AREAS of this action was to establish the levels of analysis necessary in the preparation of SIPs. Priority I designation was assigned where pollutant concentrations at certain levels above the NAAQS were measured. In the absence of such data, AQCRs containing urban centers with 1970 populations exceeding 200,000 were also included. For those pollutants designated Priority III, no analysis was required for the SIP element from that AQCR. Within the State of Colorado, only Metropolitan Denver Intrastate AQCR was designated a Priority I. Specific pollutants so labeled were CO and O_x.

In 31 metropolitan areas throughout the U.S., implementation of stringent stationary source and vehicle emissions controls will produce reductions insufficient to attain the NAAQS. In those areas Transportation Control Plans (TCP) are required as part of the SIP. The Metropolitan Denver AQCR has been identified by EPA as subject to this requirement.

In further satisfaction of its charter, EPA is also charged with identifying geographical areas where the potential exists for violation of the NAAQS in the years following initial attainment. For these areas, designated as Air Quality Maintenance Areas (AQMA), states must include within their air quality implementation plans additional measures to insure continued adherence to the NAAQS. These additional measures comprise the Air Quality Maintenance Plan (AQMP). The Metropolitan Denver AQCR is also subject to this requirement for transportation-related pollutants, CO, O_x, and NO_2.

2) Transportation Regulations

In 1973 the Federal-Aid Highway Act added Section 109(j) to 23 U.S.C. 134, which directed the Department of Transportation to develop guidelines to assure that highways constructed with Federal funds are consistent with any approved plan for attainment of the NAAQS. On 26 November 1974, the FHWA published final regulations setting forth these procedures.

Also pursuant to the 1973 Federal-Aid Highway Act, within each geographical area an agency must be designated as responsible for conducting the "continuing, comprehensive and cooperative" transportation planning process. Such an agency is referred to in generic terms as a Metropolitan Planning Organization (MPO).

In Colorado the Governor was responsible for the designation of MPOs throughout the state. In the Metropolitan Denver region, the Joint Regional Planning Program (JRPP) was appointed the MPO. A more detailed discussion of the JRPP will be presented later in this section.

In order to assure conformity of transportation planning to federal highway and air quality standards, the FHWA, through its 1974 guidelines, requires that local highway agencies in cooperation with local planning agencies establish a continuing review procedure with the local air pollution control agency. The purpose of this review procedure is to assess the consistency of the transportation plan with the approved SIP. In the Metropolitan Denver region, the Colorado Division of Highways (CDH) is the local highway agency, the JRPP, as the MPO, is the local planning agency, and the Air Pollution Control Division (APCD) of the Colorado Department of Health is the local air pollution control agency.

The CDH is required to request the MPO (JRPP) to determine annually the consistency of the transportation plan to the SIP. After review by the APCD, the Regional Federal Highway Administrator, in consultation with the Regional Administrator of the EPA, will annually assess the degree of coordination in the planning process between transportation and air quality and review the determination on consistency between the transportation plan and the SIP. The full review process is outlined diagrammatically in Figure C-2, from Reference 1.

b. Joint Regional Planning Program (JRPP)

As a result of the 1973 Federal-Aid Highway Act, it became necessary for the Governor of Colorado to designate for each region in the state a Metropolitan Planning Organization (MPO). It was to be the responsibility of these agencies to conduct the "continuing, comprehensive and cooperative" transportation planning process mandated by that law (23 U.S.C. 134).

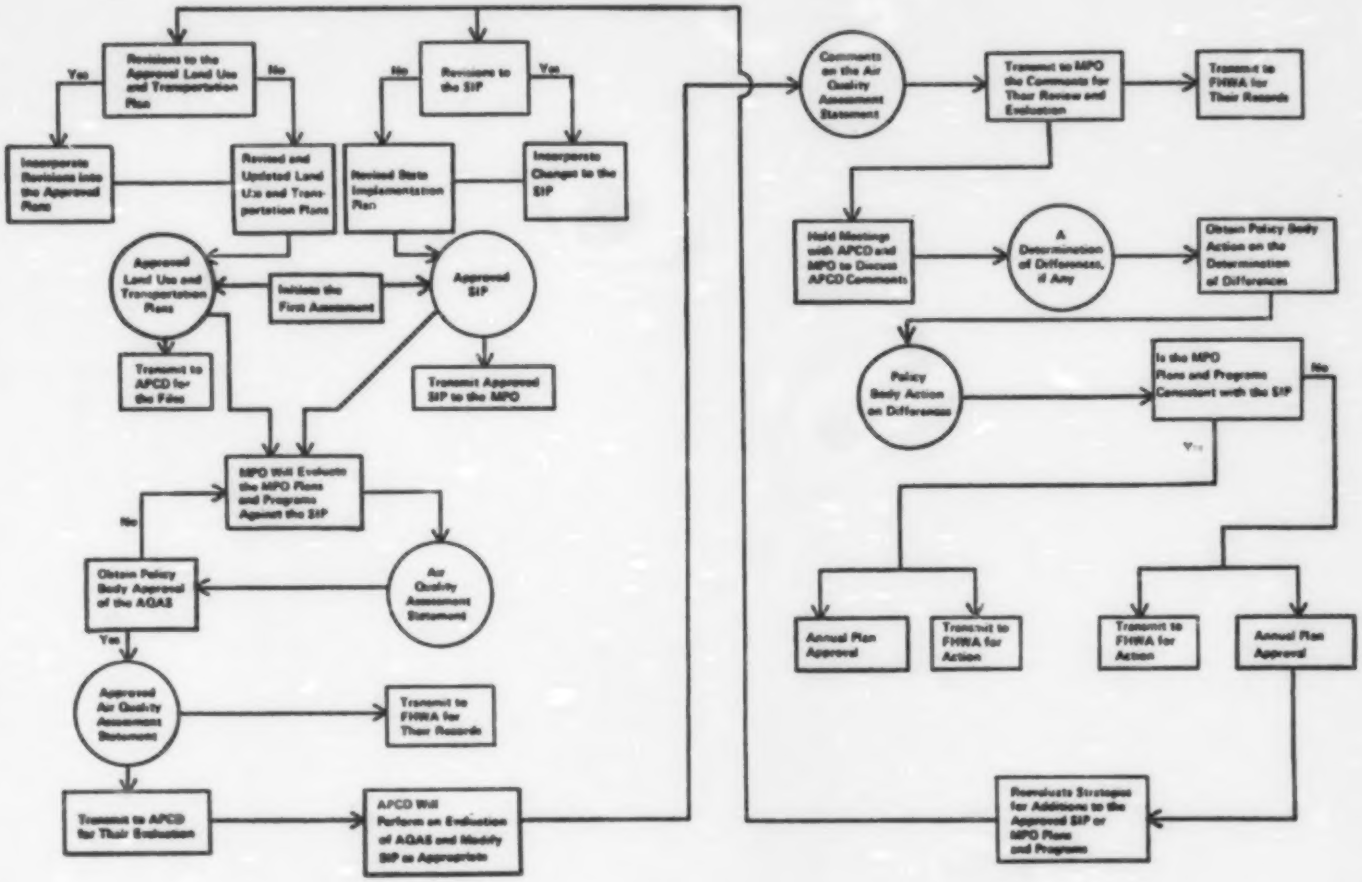

Revisions to the Approved Land Use and Transportation Plan
Yes
No
Incorporate Revisions into the Approved Plans
Revised and Updated Land Use and Transportation Plans
Revisions to the SIP
No
Yes
Revised State Implementation Plan
Incorporate Changes to the SIP
Approved Land Use and Transportation Plans
Initiate the First Assessment
Approved SIP
Transmit to APCD for the Files
Transmit Approved SIP to the MPO
MPO Will Evaluate the MPO Plans and Programs Against the SIP
No
Obtain Policy Body Approval of the AQAS
Air Quality Assessment Statement
Yes
Approved Air Quality Assessment Statement
Transmit to FHWA for Their Records
Transmit to APCD for Their Evaluation
APCD Will Perform an Evaluation of AQAS and Modify SIP as Appropriate
Comments on the Air Quality Assessment Statement
Transmit to MPO the Comments for Their Review and Evaluation
Transmit to FHWA for Their Records
Hold Meetings with APCD and MPO to Discuss APCD Comments
A Determination of Differences, if Any
Obtain Policy Body Action on the Determination of Differences
Policy Body Action on Differences
Is the MPO Plans and Programs Consistent with the SIP
No
Yes
Annual Plan Approval
Transmit to FHWA for Action
Transmit to FHWA for Action
Annual Plan Approval
Reevaluate Strategies for Additions to the Approved SIP or MPO Plans and Programs

FIGURE C-2. AIR QUALITY REVIEW PROCEDURE FLOW CHART

Throughout the state, then-Governor John Vanderhoof, who had just succeeded Governor John Love upon his resignation to assume federal responsibilities in Washington, D. C., appointed MPOs in conformity with the guidelines provided. In all regions, with the exception of the Metropolitan Denver region, he named as MPO the local council of governments. In the Denver/Boulder region, however, he designated as MPO a hybrid agency called the Joint Regional Planning Program (JRPP), consisting of the Denver Regional Council of Governments (DRCOG), which he specified as the Policy Body, the Colorado Division of Highways (CDH), and the Regional Transportation District (RTD).

The structure of the JRPP was outlined in a Memorandum of Agreement with working responsibilities included in an Operations Plan. Under federal guidelines, decisionmaking authority was vested in the Regional Director, consisting of those individuals or individual as outlined in the Memorandum of Agreement. In the JRPP the Regional Director contained representatives from all three member agencies. Originally, membership consisted of the executive directors of each agency. However, in February of 1976, an amendment to the Memorandum of Agreement revised the membership, expanding it by four members--the chairman of the state highway commission, the RTD chairman, and two DRCOG officials who are also local elected officials. The latter two officials were DRCOG Chairman Don DeDecker, a Lakewood city councilman, and DRCOG Vice-Chairman James Nolan, a Denver city councilman. Since that time, the final Regional Director configuration has consisted of seven members, four from state agencies and three from the DRCOG.

The JRPP had been in existence prior to its designation as the Metropolitan Denver MPO. It began formally on 16 April 1971, and the original objectives of its program were: (1) to integrate regional transportation planning with other elements of the comprehensive planning process; (2) to meet the planning requirements of the 1962 Federal Aid Highway Act and the 1964 Urban Mass Transit Act; (3) to develop, update and adopt transportation and land use plans; (4) to translate plans into priority programs; and (5) to develop a continuing long range comprehensive and transportation planning capability within the DRCOG, to serve the future planning needs of both the CDH and the RTD.

In October of 1973, the JRPP published a draft summary report prepared by the staff of the DRCOG which set forth concepts for land use, highways, and public transportation. These are presented, for the JRPP planning area shown in Figure C-3, in Figures C-4 through C-6.

Having outlined above the general structure of the JRPP, it is now important to examine its infrastructure as it pertains to air quality. The FHWA, through its 1974 guidelines, requires for the Metropolitan Denver region coordination in the transportation planning process between the CDH and the JRPP, as the MPO. Major responsibility is placed on the CDH for incorporating air quality considerations into transportation planning. In cooperation with the MPO, CDH must insure that land use and transportation planning pursuant to 23 U.S.C. 134 is coordinated with air quality planning conducted pursuant to 42 U.S.C. 1857 (Section 108 of the Clean Air Act of 1970). A continual review procedure is also required to assess the consistency of transportation plans with the State Implementation Plan (SIP).

In order to implement this review procedure, an Air Quality Technical Advisory Committee (AQTAC) has been formed within the JRPP. This is possible because CDH is itself a member of the JRPP. The committee consists of representatives from EPA, FHWA, APCD, and the Regional Review Team (RRT). The AQTAC should be regarded as an advisory committee to the RRT. How the AQTAC fits into the JRPP organizational structure is shown in Figure C-7, from Reference 1. Functionally, the AQTAC serves in an advisory capacity to the RRT. As such, its comments and advice need be considered by the RTT as only informal and advisory.

The final air quality output of the JRPP transportation review is an Air Quality Assessment Statement (AQAS). A number of criteria of consistency with the SIP, all detailed in joint FHWA/EPA guidelines (Reference 2), must

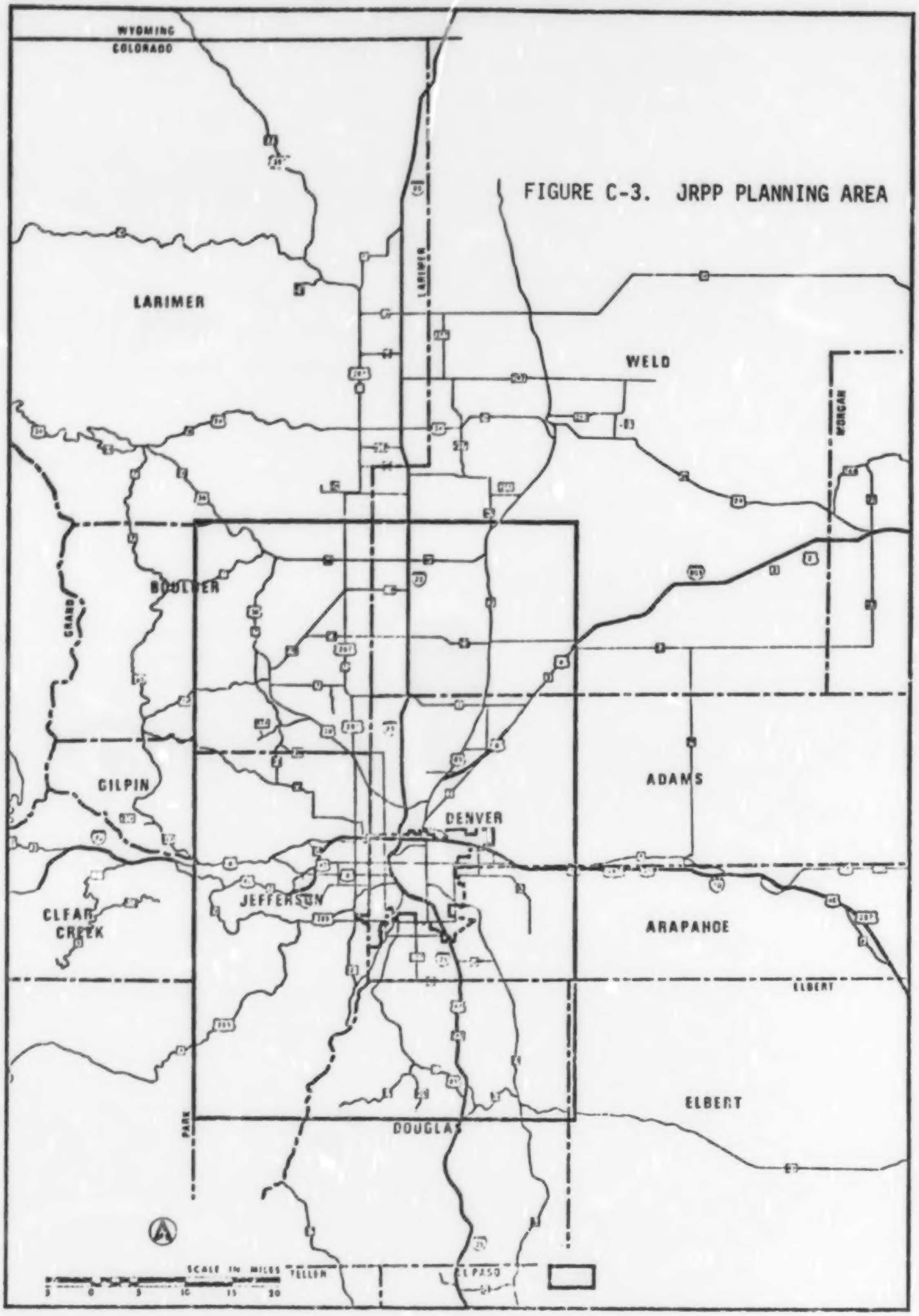


FIGURE C-3. JRPP PLANNING AREA

WYOMING
COLORADO
LARIMER
WELD
MORGAN
BOULDER
GRAND
GILPIN
ADAMS
DENVER
CLEAR CREEK
JEFFERSON
ARAPAHOE
ELBERT
DOUGLAS
PARK
TELLER
EL PASO
SCALE IN MILES
5 0 5 10 15 20

Reproduced from
best available copy.

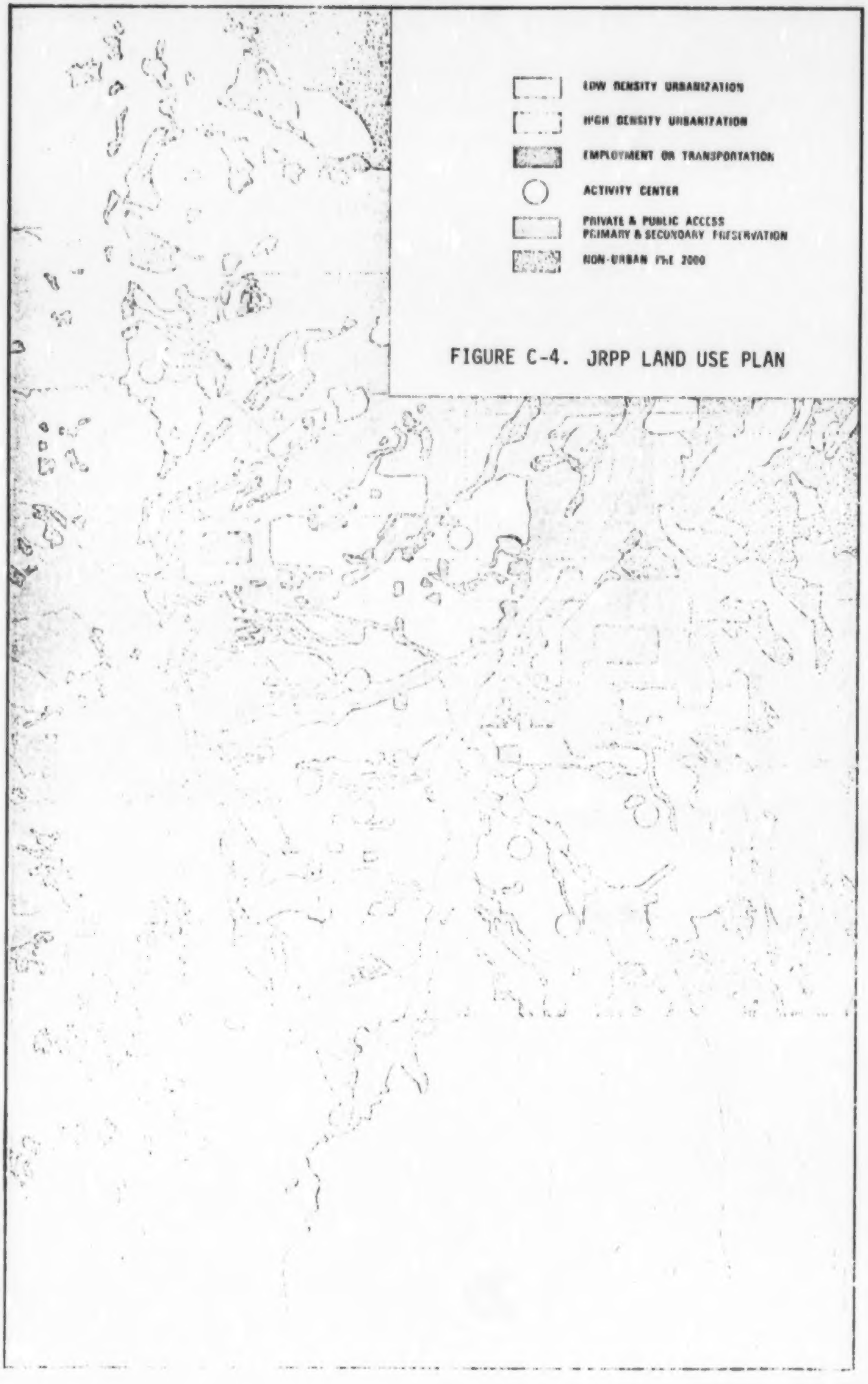

LOW DENSITY URBANIZATION
HIGH DENSITY URBANIZATION
EMPLOYMENT OR TRANSPORTATION
ACTIVITY CENTER
PRIVATE & PUBLIC ACCESS PRIMARY & SECONDARY PRESERVATION
NON-URBAN PRE 2000

FIGURE C-4. JRPP LAND USE PLAN

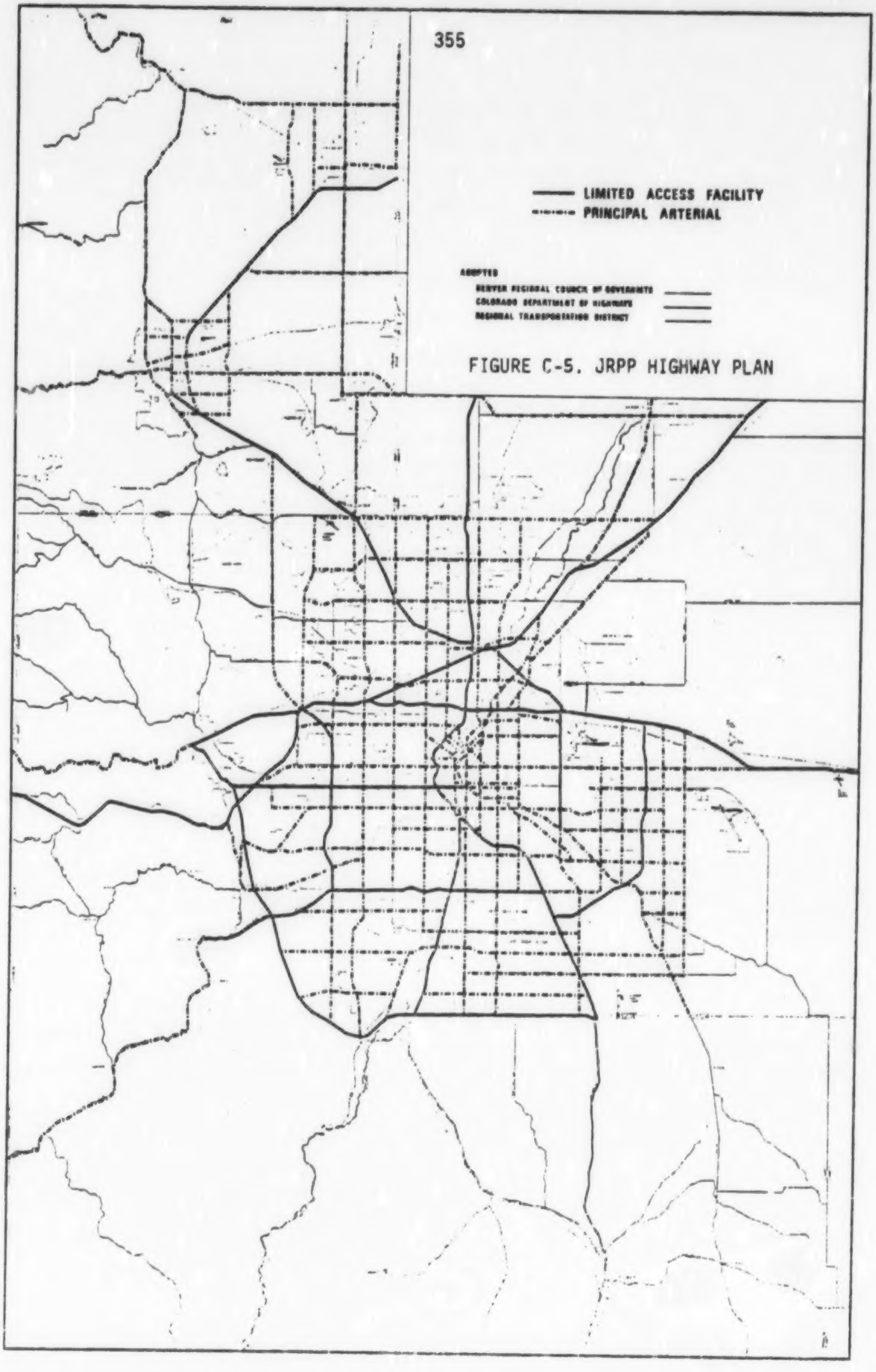

LIMITED ACCESS FACILITY
PRINCIPAL ARTERIAL
ADOPTED
DENVER REGIONAL COUNCIL OF GOVERNMENTS
COLORADO DEPARTMENT OF HIGHWAYS
REGIONAL TRANSPORTATION DISTRICT

FIGURE C-5. JRPP HIGHWAY PLAN

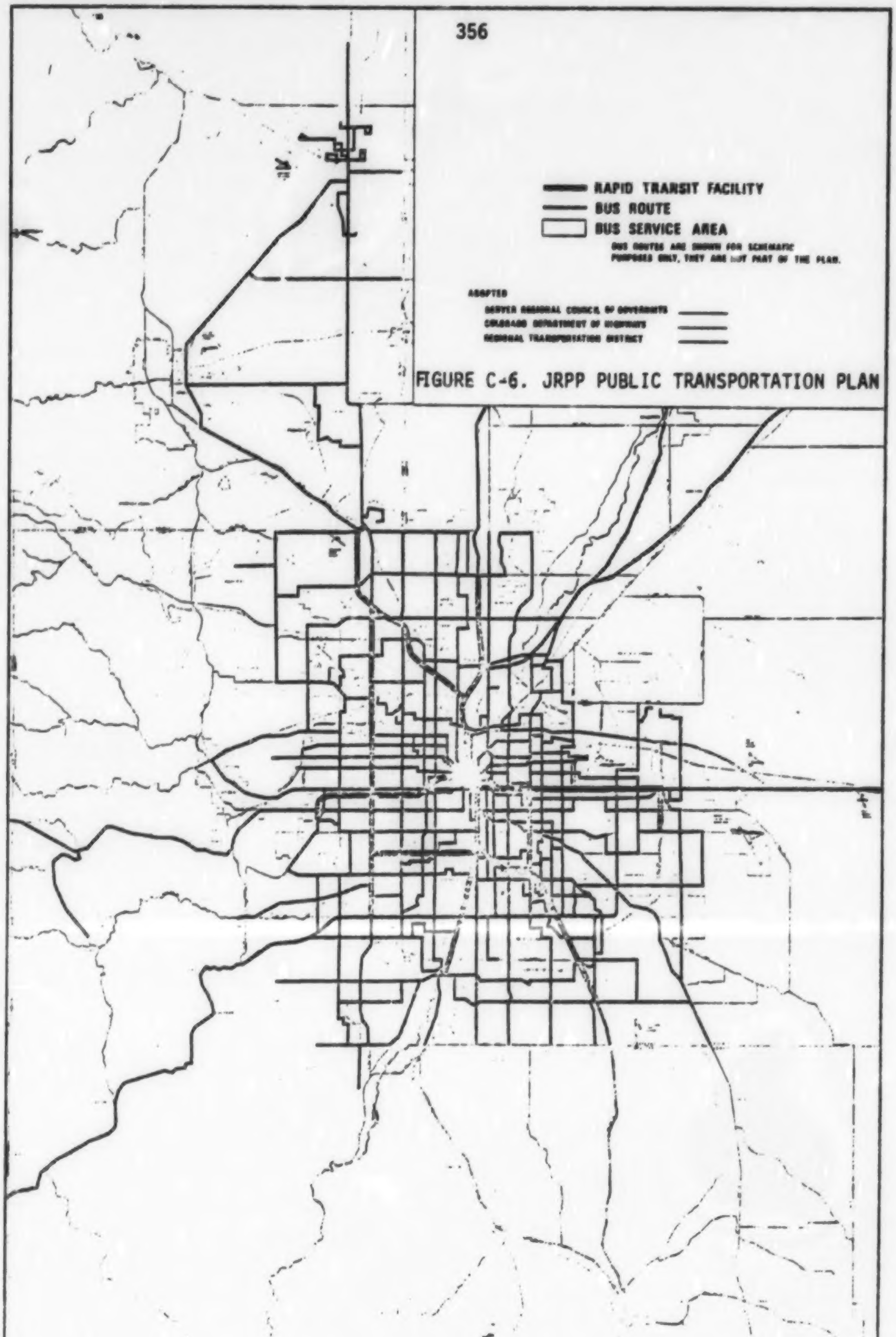

RAPID TRANSIT FACILITY
BUS ROUTE
BUS SERVICE AREA
BUS ROUTES ARE SHOWN FOR SCHEMATIC PURPOSES ONLY, THEY ARE NOT PART OF THE PLAN.
ADOPTED
DENVER REGIONAL COUNCIL OF GOVERNMENTS
COLORADO DEPARTMENT OF HIGHWAYS
REGIONAL TRANSPORTATION DISTRICT

FIGURE C-6. JRPP PUBLIC TRANSPORTATION PLAN

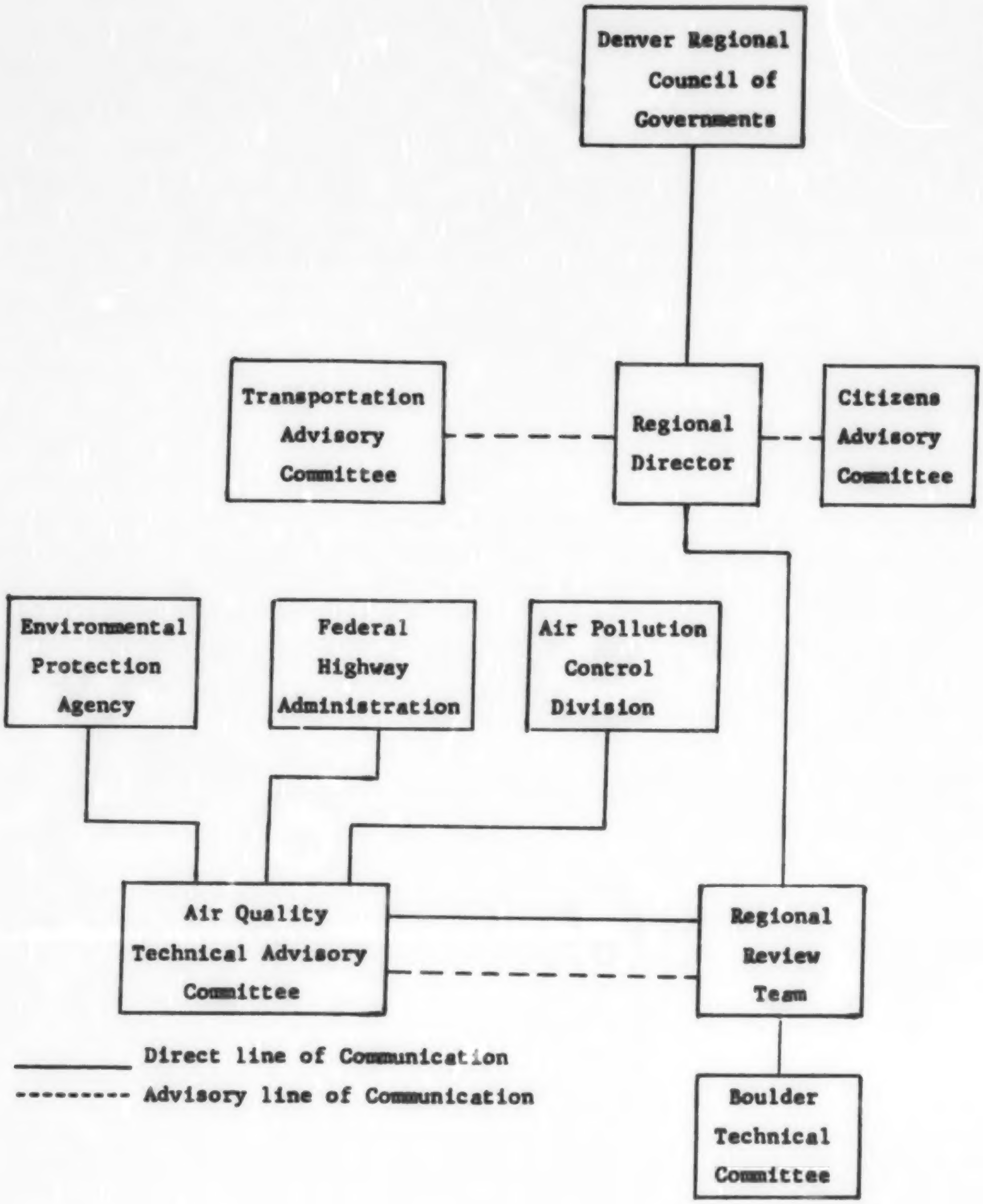

Denver Regional Council of Governments
Transportation Advisory Committee
Regional Director
Citizens Advisory Committee
Environmental Protection Agency
Federal Highway Administration
Air Pollution Control Division
Air Quality Technical Advisory Committee
Regional Review Team
Boulder Technical Committee
Direct line of Communication
Advisory line of Communication

FIGURE C-7. JRPP ORGANIZATIONAL STRUCTURE--AIR QUALITY be addressed by the JRPP, as the MPO. These include SIP investigation strategies, such as stationary hydrocarbon control, gasoline limitation, bus/carpool lanes, parking limitation, and mass transit improvements. The final form of the AQAS, arrived at by the review procedure detailed in Figure C-2, is subject to review by the APCD.

c. Denver Regional Council of Government (DRCOG)

When the JRPP was named by the Governor as the MPO in the Metropolitan Denver region, pursuant to the 1973 Federal-Aid Highway Act, he designated the Denver Regional Council of Governments as its Policy Body. As such it has considerable influence on the transportation planning process. In practical terms, because of the size of its staff and the resources they command in technical training and access to computing facilities and mathematical modeling tools, the DRCOG plays a central role in all JRPP planning efforts. Due to the intent of its original charter in 1971, the JRPP itself has few formal staff members not simultaneously serving in other capacities within member agencies.

The composition of the DRCOG underscores the uniqueness of its position. Among those agencies comprising the JRPP, only the DRCOG has the direct, majority participation of locally elected officals. Members of the DRCOG, all elected officials in their own right, are appointed to the Council from the city councils and boards of supervisors representing the cities and counties comprising the Metropolitan Denver region.

Numerical composition is so structured that no individual city can dominate voting on the Council. Similarities both in attitude and lifestyle, however, would suggest certain regional communities of interest. Issues of importance to the downtown, highly urbanized portion of Denver, for instance, may not be emphasized to the same degree in the smaller, more surburban areas surrounding the city. Members from the outlying suburbs, together constituting a majority on the Council, could be expected to represent actively the interest of their constituents. To find such an emphasis in the planning process conducted by the DRCOG would not be unexpected.

The DRCOG is headed by a chairman and vice-chairman, as well as a six-person executive committee. Currently, Don DeDecker, a city councilman from Lakewood, is serving as Chairman, and James Nolan, a Denver city councilman is the Vice-Chairman. Robert Farley, as Executive Director, heads the DRCOG staff, assisted by David Klotz, the Deputy Executive Director. Meetings, held monthly, are attended by a number of Council members. For the meeting held on 20 October, for example, more than twenty members were present.

The part played by the DRCOG in the regional planning process has been institutionally endorsed not only by its own Articles of Association but also by federal and state law as well as by contractual agreements with the U.S. Department of Housing and Urban Development, the Department of Transportation, and the Environmental Protection Agency. In its planning role the DRCOG has addressed the forecasting of regional population and its allocation, land use, and transportation network planning. Though no specific sanctions exist requiring the conformance of local communities to DRCOG adopted plans, considerable indirect leverage towards compliance does exist. These same forecasts are used by transportation, water supply, and wastewater treatment agencies in their facilities and service planning. An individual community in search of state or federal assistance, whose planning is not consistent with DRCOG-approved plans, may find such funding denied. The level to which DRCOG regional planning extends is indicated in Figure C-8, taken from Reference 7.

To date the DRCOG has adopted a number of the component parts of its regional development plan. Since population projections serve as the basis for nearly all major planning decisions, initial attention was turned to a regional population forecast. Developed in 1971-72 and subsequently adopted on January 17, 1973, such a forecast of population level was used as the basis for land use, highway and transit plans. Adoption of the forecast marked official endorsement of a year 2000 population of 2,350,000 for the five-county

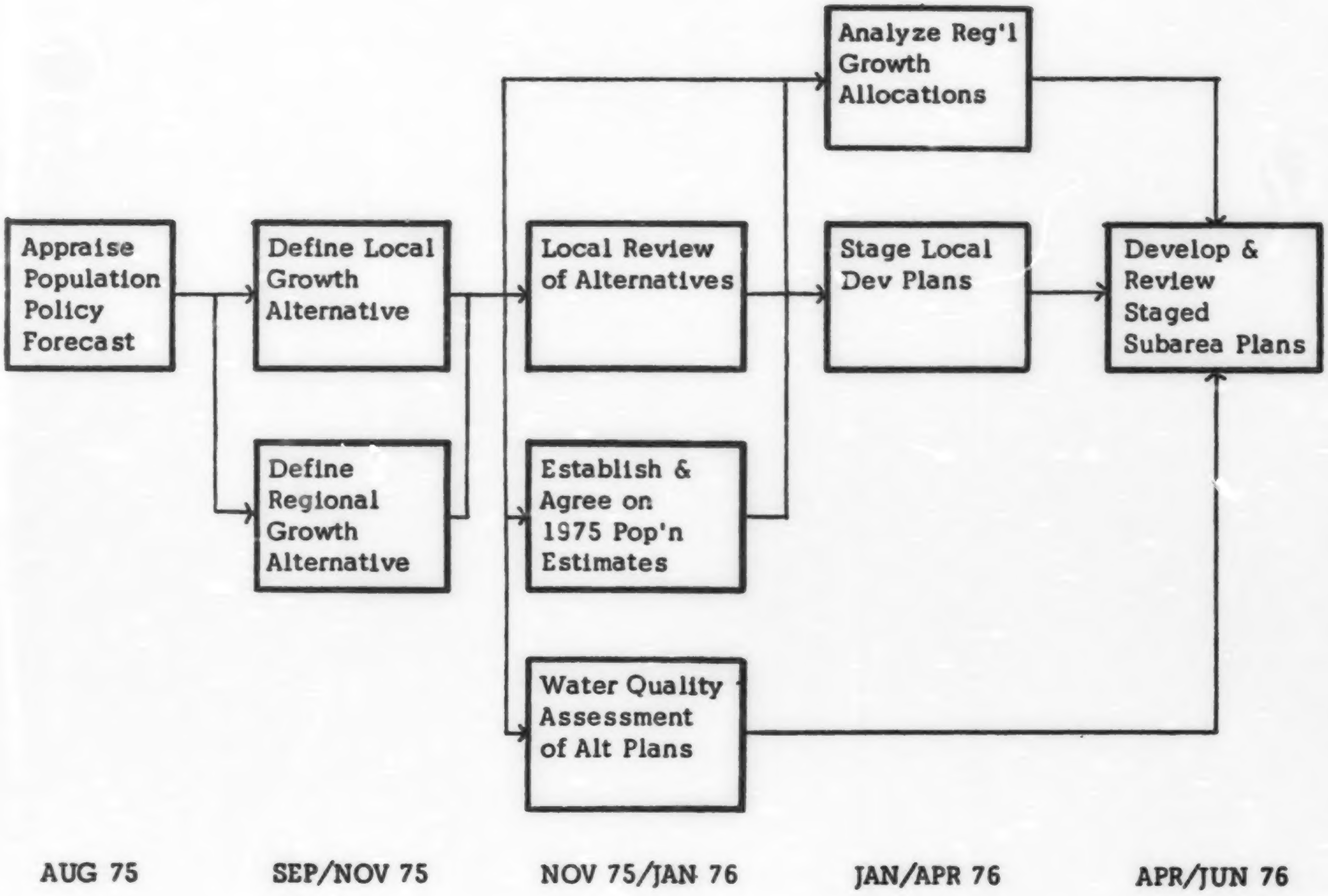

Appraise Population Policy Forecast
Define Local Growth Alternative
Define Regional Growth Alternative
Local Review of Alternatives
Establish & Agree on 1975 Pop'n Estimates
Water Quality Assessment of Alt Plans
Analyze Reg'l Growth Allocations
Stage Local Dev Plans
Develop & Review Staged Subarea Plans
AUG 75
SEP/NOV 75
NOV 75/JAN 76
JAN/APR 76
APR/JUN 76

FIGURE C-8. SUBAREA POPULATION ALLOCATION PROCESS

Denver Metropolitan area. Having agreed to a population level, efforts by the Council to agree on where that population will live have been conducted. Several iterations on an allocation plan have been performed by the DRCOG staff since the initial Council directive in October of 1975. Agreement, however, on a subarea allocation plan was finally achieved with Resolution 18, 1976, adopted by the full Council on 18 August. The specifics of these population level and allocation plans will be discussed in detail in Section 3.

The population level forecast adopted in early 1973 was subsequently used to develop regional transit and land use policy. Incorporating the forecast, the DRCOG formally adopted on 19 December 1973 the Regional Land Use, Highway and Public Transportation Plans. The land use and highway plans became JRPP policy when, in January 1974, they were endorsed by both the Colorado Division of Highways and the Regional Transportation District.

Insofar as air quality planning is concerned, DRCOG, acting as the policy arm of the JRPP, plays a major role in the joint CDH/MPO assessment of transportation plan consistency with the SIP. The review procedure, described in the discussion of the JRPP presented earlier in this section, draws heavily upon the staff resources of the DRCOG. Among their responsibilities, DRCOG staff include the development and application of computerized transportation models. To enhance and refine the accuracy of the level and distribution of vehicle-miles-traveled (VMT) projections has required continuing evolution in the modeling process. A detailed discussion of transportation modeling progress has been deferred until Section 3. It is sufficient at this point simply to recognize that any air quality assessment must be regarded as acutely sensitive to the certainty with which VMT projections are viewed.

d. Colorado Division of Highways (CDH)

The Colorado Department of Highways, Division of Highways (CDH), is another of the three member agencies comprising the JRPP. The Department of Highways is currently headed by its Executive Director, Jack Kintslinger.

As a basic charter it is charged with the primary responsibility for initiating and carrying forward the construction or reconstruction of highway sections. The Federal-Aid Highway Act of 1973 as implemented in FHWA guidelines established the additional requirement that the CDH take steps to assume consistency with the SIP for any highway construction involving federal funding. Furthermore, in cooperation with the JRPP, as MPO, the CDH must insure this planning compatibility by entering into an annual review procudure with the Air Pollution Control District.

In fulfilling their air quality responsibilities, the staff of the CDH has also acquired and supports the use of the SAI urban airshed modeling program. Most recently, the SAI model was used on a regional basis, in conjunction with the California Line Source Model (CALINE2) for microscale analysis, to develop the air quality assessment component of the Detailed Assessment Report for the Interstate 470 Project, a proposed circumferential highway around Southwest Metropolitan Denver.

The I-470 Project has long been a part of CDH plans. In 1972 a Final Environmental Impact Statement was submitted for FHWA review. The conclusions of this review (September 1974) were that significant deficiencies and questions remained regarding air quality, alternative modes of transportation, alternative highway alignments, and effects on land use. A revision of the EIS was required by the FHWA. An I-470 Ad Hoc Commission was set up by the Governor to study and make recommendations on the I-470 question.

The first major phase of that review, the Preliminary Screening Process, was completed on 30 January 1976. The Report evaluated eleven highway alternatives based on 23 environmental and transportation assessment criteria. The second major phase, the Detailed Assessment, then analyzed the remaining five feasible highway alternatives. Originally scheduled to be completed in May, 1976, the final date was extended to August by the passage of the 1976 Federal-Aid Highway Act, which enabled the consideration of federal funding for other road system alternatives.

Similar reviews must be undertaken by CDH for all major highway projects. The air quality assessment component can be expected to play a similarly significant role. As a consequence the CDH staff will maintain air quality analysis capability.

e. Regional Transportation District (RTD)

The Regional Transportation District is one of the three member agencies comprising the JRPP. Its enabling legislation provides that RTD shall develop, operate, and maintain a mass transportation system for the District, which presently is comprised of the City and County of Denver, Boulder and Jefferson Counties, the western portions of Adams and Arapahoe Counties, and the northeastern portion of Douglas County. Jurisdictional boundaries are as shown in Figure C-9, from Reference 12.

The enabling statute provided for the development and adoption of a comprehensive transit plan. Also, in addition to providing for the collection of certain tax revenues in support of transit activities, it called for a referendum on bond issuance authority. Such a referendum was held on September 7, 1973, with the voters of the region authorizing the issuance of up to $425,000,000 in sales tax revenue bonds. They also approved a ballot issue which specified the development of a multi-modal mass transportation system for the region. The Public Transportation Plan for the Year 2000, as adopted and amended by the JRPP, provided the framework within which RTD efforts were directed.

The long-range plans of the RTD contemplate a high level of bus service between communities within the district, and community level circulator service designed to provide a collection and distribution complement to the rapid transit portion of an integrated multi-modal system. The bus fleet presently operated by RTD consists of 517 vehicles. Accounting for the orderly retirement and replacement of vehicles, the RTD plans to expand the fleet by approximately 28 vehicles each year, bringing the total to 799 by 1985. Funding assistance has been sought from the federal government through UMTA.

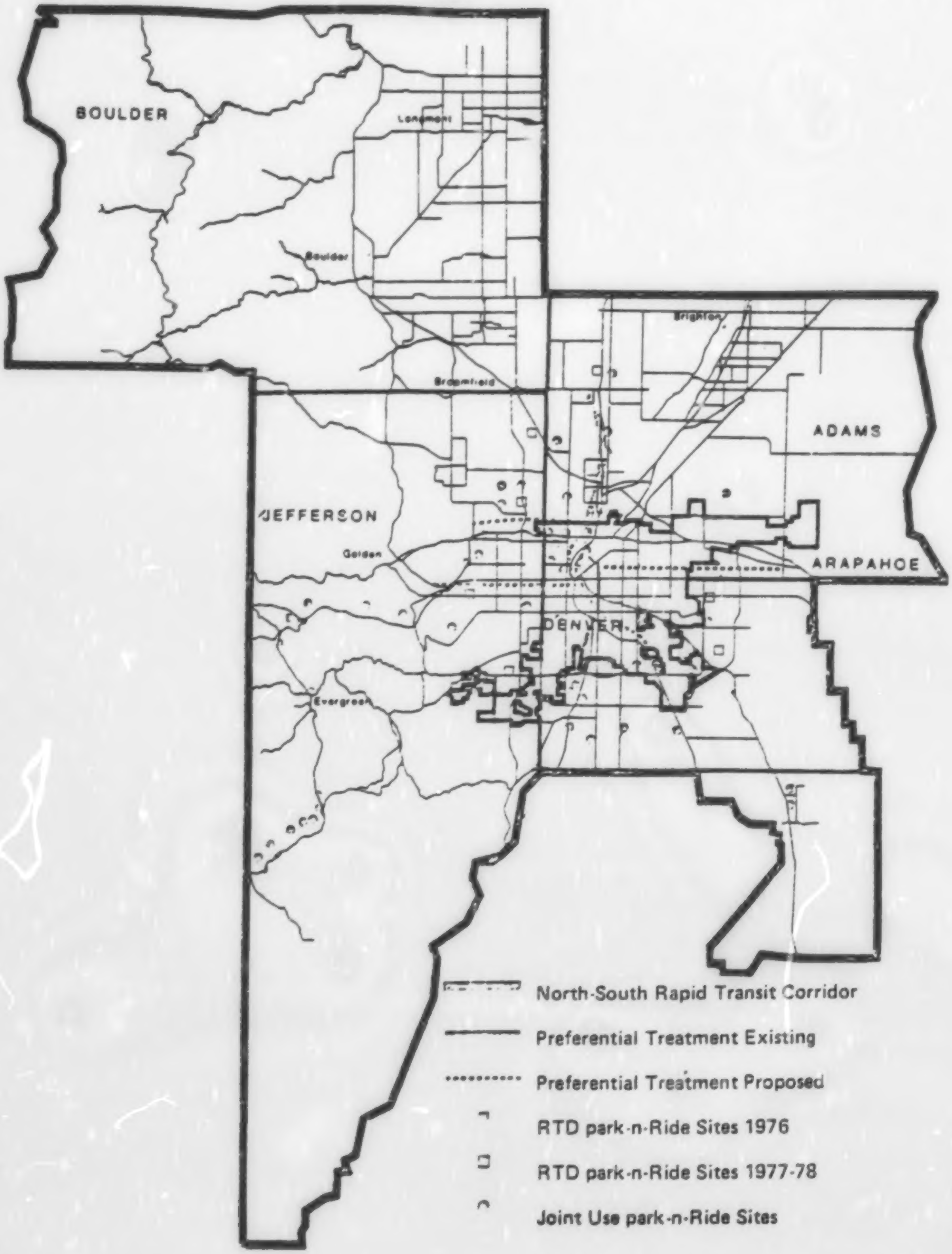

BOULDER
Longmont
Boulder
Brighton
Broomfield
ADAMS
JEFFERSON
Golden
ARAPAHOE
DENVER
Evergreen
North-South Rapid Transit Corridor
Preferential Treatment Existing
Preferential Treatment Proposed
RTD park-n-Ride Sites 1976
RTD park-n-Ride Sites 1977-78
Joint Use park-n-Ride Sites

FIGURE C-9. RTD JURISDICTIONAL BOUNDARIES

In addition to bus service, the RTD has been considering for several years various alternative fixed rapid transit networks. On promising heavy traffic corridors, a number of candidate systems were investigated, including light rail transit (LRT), conventional rail transit, automated rapid transit (ART), and personalized rapid transit (PRT). The RTD board on 12 February 1976 acted to endorse an LRT plan on the most promising guideway corridor. The selected network, shown in Figure C-10 from Reference 13, consisted of 14 stations extending over a north-south alignment 22 miles long.

The system cost for the RTD-selected alignment, shown in Table C-1 from Reference 12, totals $492,000,000 in December 1974 dollars. Of this amount the fixed facility portion is $391,000,000. Federal funding assistance was sought by RTD through UMTA.

TABLE C-1. RTD-SELECTED RAPID TRANSIT PROJECT COST

		DOLLARS (MILLIONS)
Guideway		153
Trackwork		28
Stations		64
Station Parking		9
Control System		23
Electrification		28
Yard & Shops		34
Adm. & Control Facility		10
Right-of-Way		42
	Sub-Total	391
Vehicles		35
System Verification Test		11
Program Management		55
	Sub-Total	101
(December 1974 Dollars)	TOTAL	492

After review of the RTD proposal, on 29 June 1976 in a letter to John Crowley, Chairman of the RTD, Robert Patricelli, the Administrator for UMTA, informed the RTD of UMTA's decision concerning federal funding

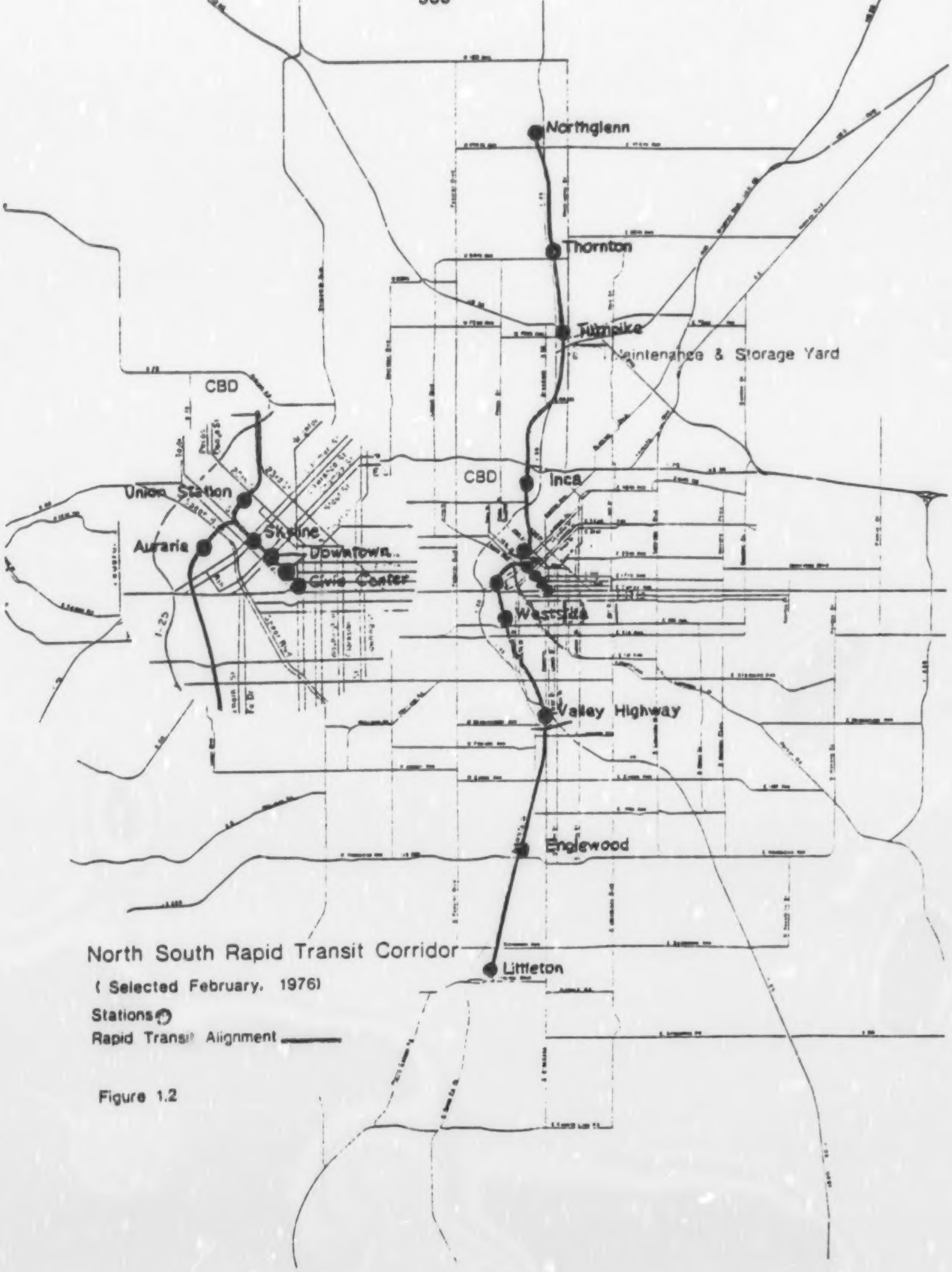

Northglenn
Thornton
Turnpike
Maintenance & Storage Yard
CBD
CBD
Inca
Union Station
Skyline
Auraria
Downtown
Civic Center
I-25
Westside
Valley Highway
Englewood
Littleton
North South Rapid Transit Corridor
(Selected February, 1976)
Stations
Rapid Transit Alignment
Figure 1.2

FIGURE C-10. RTD-SELECTED RAPID TRANSIT PLAN of the 22-mile light-rail line. The conclusions were threefold: first, that it was premature for the Federal Government to provide engineering or construction funds for the development of the proposed line; second, that UMTA was prepared to loan advance right-of-way acquisition funding to allow RTD to hold such property until the need for a fixed guideway system might become more pronounced; and, three, that UMTA was willing to consider substantial funding for future bus system improvments. The action detailed in this letter can be expected to cause a substantial reassessment by the RTD of their regional transportation plans. A reorientation towards an all-bus transit system seems a likely course of action. The amount of funding made available under the third point above has been said to be in the neighborhood of $200,000,000 or less than half the RTD request for the light-rail system.

A few words are in order about RTD planning efforts having either direct or indirect effect on regional air quality. As will be explained in more detail in Section 3, several iterations of population allocation, land use, and transportation plans exist within various agencies, each an evolutionary extension of their predecessor. In conducting planning efforts, however, planners have no choice but to use those versions currently most accepted at the time the study is conducted. These planning efforts, consequently, are accurate only to the extent their assumptions still agree with new population, land use, and transportation plan assumptions.

System planning by the RTD has been done using a relatively early population allocation version. Of the three major population allocation versions, Cycle 3 and Cycle 4 (both generated using a computerized population allocation model called EMPIRIC) and the Subarea Allocation Plan recently considered by the JRPP/DRCOG, the version known as Cycle 3 was used by the RTD. Changes in allocation have since occurred, particularly in the southwestern portion of the Denver region (southeastern Jefferson County).

The design of any regional transit system and its ameliorating effects on air quality is sensitive to the highway system on which that transit system must operate. The JRPP has adopted a Year 2000 Transportation Plan which details their projected roadway network. However, in the event that the JRPP plan is substantially overbuilt and that the funding program necessary for its construction is an unrealistically ambitious one, RTD planning has been conducted using a more modest highway system known as the Existing plus Committed (E+C) network. Basically, it consists of those highway elements already built or for which funds have already been committed. This is an inconsistency with CDH highway planning, which, though also assuming Cycle 3 population allocation, assumes the Year 2000 JRPP highway plan. The extent of these differences on plan compatibility remains unanswered in any definitive way. It was, in fact, cited by the FHWA as a factor in their recent alteration of JRPP certification as MPO. The ultimate effects on air quality projections for the Denver region also remain unassessed.

f. Air Pollution Control Division (APCD)

Under the 1974 federal guidelines established by the FHWA pursuant to the 1973 Federal-Aid Highway Act, the Air Pollution Control Division plays an important role in verifying the consistency of regional transportation plans to the State Implementation Plan for air quality attainment and maintenance. It is charged with reviewing on a continual basis the transportation plans of the CDH and the JRPP, as MPO.

In terms of jurisdictional responsibilities the APCD, a part of the Colorado Department of Health, is responsible for enforcement of the regulations and standards as developed and adopted by the Air Pollution Control Commission (APCC). The full regulatory framework of Colorado's air quality program was established by the Colorado Air Pollution Control Act of 1970. The administrative structure set up by the Act consists of the APCC, with broad rulemaking authority, the Air Pollution Variance Board, with rule suspension authority, and the APCD, with enforcement capability. The 1970 enabling legislation organized all three within the Colorado Department of Health.

Among their responsibilties, it is the function of the APCD to enforce stationary source controls; to reduce or plan for the eventual reduction of mobile source emissions; to monitor pollutants; and to allocate air quality program resources and plan for the attainment of the NAAQS. The APCD is provided an engineering staff to support the enforcement effort.

The surveillance of statewide air quality conducted by the APCD represents the major source of air quality data in the Metropolitan Denver region. Because of their Priority I designation in the Denver AQCR, emphasis is placed on carbon monoxide (CO), oxidant (O_3), and particulates. The basic monitoring network maintained by the APCD is shown in Figures C-11 and C-12, from Reference 16.

Over fifty percent of the population in Colorado resides within the Denver AQCR. The high vehicle usage, combined with three major power plants, two oil refineries and a number of other medium sized to large industrial sources, results in a serious air quality problem. A breakdown of both the size and source of pollutants within the Denver AQCR is shown in Table C-2, from Reference 16.

TABLE C-2. DENVER AQCR - SIGNIFICANT POINT SOURCES

SOURCE TYPE	NUMBER	TOTAL EMISSIONS, EACH POLLUTANT TONS/YEAR	
Agricultural	9	Particulate	7,066
Mineral Processing	46	SO_2	38,852
Energy	15	CO	61,171
Industrial	38	NO_x	49,112
Miscellaneous	7	HC	5,193
	115		

The responsibility has also been assigned by the Air Pollution Control Commission to the APCD to develop and maintain the capability to model observed air quality readings. It was in this context that the APCD acquired the SAI urban airshed modeling program. It has been most recently

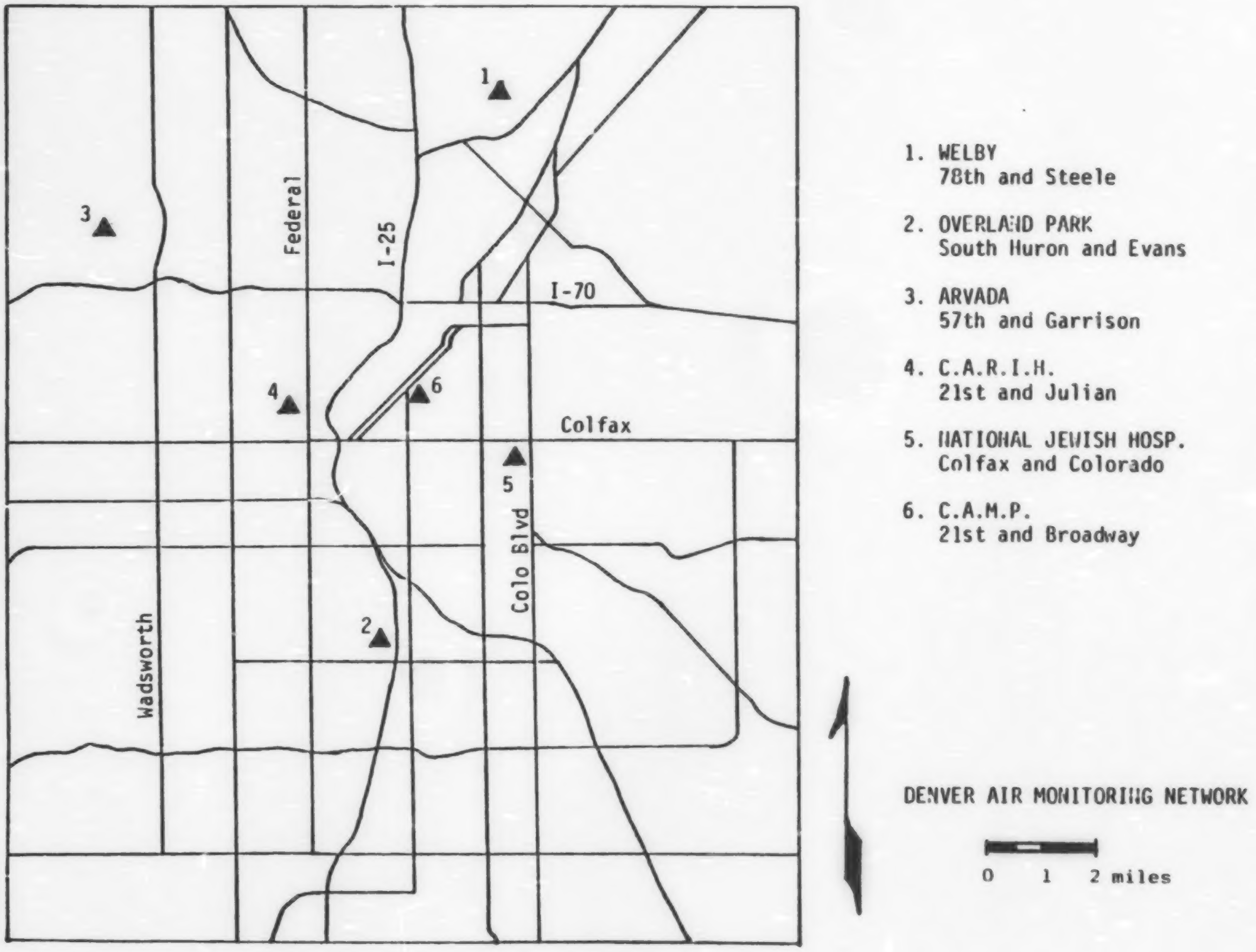

1
3
Federal
I-25
I-70
4
6
Colfax
5
Colo Blvd
2
Wadsworth
1. WELBY
78th and Steele
2. OVERLAND PARK
South Huron and Evans
3. ARVADA
57th and Garrison
4. C.A.R.I.H.
21st and Julian
5. NATIONAL JEWISH HOSP.
Colfax and Colorado
6. C.A.M.P.
21st and Broadway
DENVER AIR MONITORING NETWORK
0
1
2 miles

FIGURE C-11. APCD DENVER AIR QUALITY MONITORING NETWORK

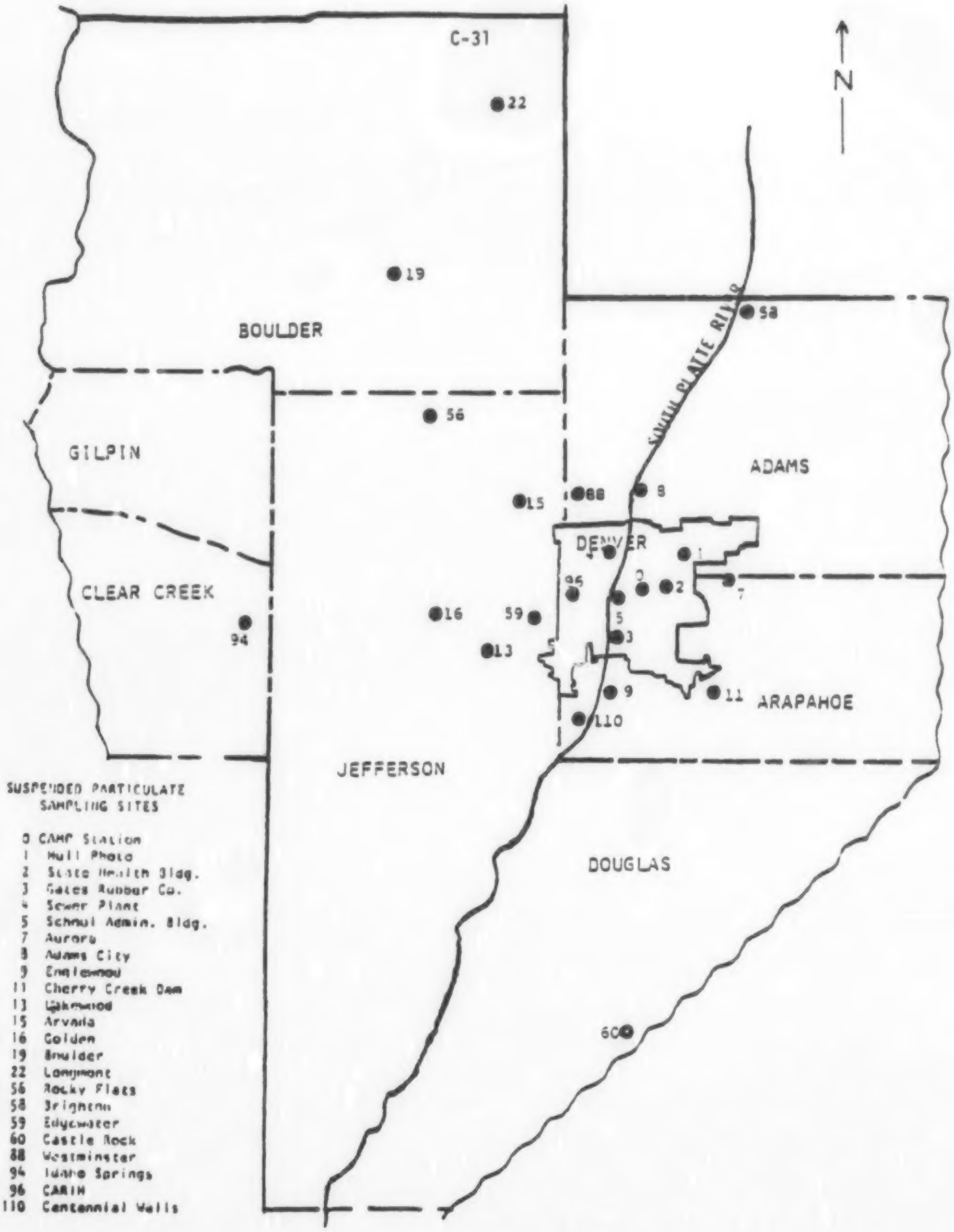

C-31
N
22
19
BOULDER
58
SOUTH PLATTE RIVER
56
GILPIN
ADAMS
88
8
15
DENVER
4
1
96
0
2
7
5
CLEAR CREEK
16
59
3
94
13
9
11
ARAPAHOE
110
JEFFERSON
DOUGLAS
60
SUSPENDED PARTICULATE SAMPLING SITES
0 CAMP Station
1 Hull Photo
2 State Health Bldg.
3 Gates Rubber Co.
4 Sewer Plant
5 School Admin. Bldg.
7 Aurora
8 Adams City
9 Englewood
11 Cherry Creek Dam
13 Lakewood
15 Arvada
16 Golden
19 Boulder
22 Longmont
56 Rocky Flats
58 Brighton
59 Edgewater
60 Castle Rock
88 Westminster
94 Idaho Springs
96 CARIH
110 Centennial Walls

FIGURE C-12. APCD DENVER REGION SUSPENDED PARTICULATE MONITORING NETWORK used by the APCD staff in an analysis of the Denver-Boulder Air Quality Maintence Area. The purpose of the study was to define the existing and projected air quality in the Metropolitan Denver region, and to determine whether the NAAQS will be attained in Denver by 1985. This assessment was performed for three years: 1974 (the baseline year), 1980 and 1985. For the latter two years, results of the SAI model were used for short-term averaging (i.e., 1 hour and 8 hours), and the Climatic Dispersion Model (CDM) was used to evaluate long-term averages (i.e., annual).

The pollutants specifically addressed were CO, O_3, NO_2, and particulates. The NAAQS for these and other pollutants are given in Annex C-2 of this report. The major assumptions in the study are outlined in Table C-3, with the final results shown in Tables C-4 and C-5. All of these are taken from Reference 16.

TABLE C-3. MAJOR ASSUMPTIONS IN APCD STUDY

Federal Motor Vehicle Control Program Assumed to be on schedule and to be Effective at this Altitude (AP-42)

Automotive Inspection/Maintenance not Assumed

City of Boulder not Included in Analysis Concentrations Calculated

Ozone from Set of Reactions Derived for Los Angeles, California

Highway and DRCOG Traffic and Population Inputs are Appropriate

No Small Scale Localized Analysis will be Performed

Phase II Vapor Recovery Strategy not Assumed

The emissions inventory developed by the APCD for use in the SAI and CDM models is presented in Table C-6, also from Reference 16. Both daily and annual figures are shown.

TABLE C-4. REGIONWIDE DENVER AIR QUALITY ATTAINMENT IN APCD STUDY

Pollutant		Status to 1985
Carbon Monoxide:	1-hour	Non-attainment
	8-hour	Non-attainment
Ozone		Non-attainment
Particulate:	24-hour	Non-attainment
	1-year	Non-attainment
NO_2		Maintenance Problem

TABLE C-5. DENVER AQMA AREA OF VIOLATION IN APCD STUDY

		SQUARE MILES OF VIOLATIONS+		
POLLUTANT		1975	1980	1985
Carbon Monoxide:	1-hour*	38	41	6
	8-hour	170	179	26
Ozone:	1-hour++	740	662	582
Particulates:	24-hour	776	900	900
	Annual	675	900	900
NO_2:	Annual	1	11	16

+Maximum Hour Violations
*Average of 0700 and 0800 Violations
++Study Day Violations

(Total Study Area 900 Square Miles)

TABLE C-6. DENVER DAILY AND ANNUAL SOURCE CONTRIBUTIONS IN 1974

(a) Daily

SOURCE CATEGORY	TOTAL TONS/DAY	% CONTRIBUTIONS
Carbon Monoxide:*		
Automotive	2925.0	94.5
Space Heat	2.9	0.1
Point Sources	167.6	5.4
	3095.5	100.0
Hydrocarbons:**		
Automotive	199.18	83.9
Space Heat	0.48	0.2
Oil Paint	2.08	0.9
Gas Stations	11.67	4.9
Cleaners	4.94	2.1
Incinerators	0.11	0.0
Point Sources	13.14	5.5
Airports	5.92	2.5
	237.52	100.0

*Based on winter emissions distributions
**Based on summer emissions distributions

(b) Annual

SOURCE CATEGORY	TOTAL TONS/YEAR	% CONTRIBUTIONS
Particulate:		
Space Heat	511	1.4
Automotive	4,213	11.9
Airports	63	0.0
Construction	8,730	24.7
Street Sanding	15,857	44.9
Point Sources	5,981	16.7
	35,355	99.6
NO_2:		
Space Heat	5,348	7.4
Small Points	87	0.0
Automotive	31,646	43.7
Airports	1,552	2.1
Point Sources	33,773	46.6
	72,406	99.8

A final word about the APCD study assumptions should be injected. As mentioned earlier, several iterations have been developed for population allocation. It appears that the APCD staff used EMPIRIC Cyle 4 projections to obtain their population data. This is at variance with most transportation modeling efforts done by the CDH and the DRCOG. Done at earlier times, these studies incorporated EMPIRIC Cycle 3 population allocation forecasts.

3. OVERVIEW OF PLANNING ISSUES

a. Planning Issues and Planning Agencies

It is not difficult to secure from most planning agencies agreement on the identity of the fundamental issues of planning. Population and land use forecasts intertwine to form the core of the planning process. Implied in each are basic decisions about human priorities. Growth--how much and where it will be distributed--dominates as a precursor to any planning study. The construction of facilities to provide public services, such as transportation, water supply, and sewerage treatment, both paces and responds to the level, distribution and staging of population growth. Sound planning can encourage the development of a sound regional ecomomic base which, by accommodating demands for new jobs, products, and services, creates a tax base healthy enough to support strong and responsible community programs.

The difficulty in any planning process, however, lies not in assessing the broad issues but rather in obtaining a consistent set of planning assumptions about the specific ones. The problem is aggravated by the evolutionary nature of planning. In response to public reexamination, planning is usually iterative. Specific studies, however, must draw on the results of predecessor studies. Planners often have no choice but to accept the best set of assumptions available at the time of the study. Consequently, the results can be regarded as accurate only to the extent the study's assumptions still agree with new population, land use and transportation plans. An ongoing assessment of consistency is thus essential in any area in which planning is subject to volatility.

In part due to the above reasons, there is a proliferation of planning alternatives, each of varying vintage, within the agencies responsible for planning in the Metropolitan Denver region. Though the DRCOG has agreed since January 1973 on a year 2000 population forecast of 2,350,000 for the five-county Denver area, several attempts have been made to allocate the new growth to individual communities. In 1972 the EMPIRIC

Activity Allocation Model was developed for the Denver region to aid in making these allocations. The two most recent applications of the model, referred to as Cycle 3 and Cycle 4, have been used by different agencies for different purposes.

Of the three population allocation forecasts, Cycle 3, Cycle 4 and the Subarea Allocation Plan recently considered by the JRPP/DRCOG, the earliest of these, Cycle 3, was used by both the CHD and the RTD for their transportation planning, although each agency used its own version. Within the Health Department, the APCD has used Cycle 4 for their transportation/air quality studies. The area source emissions inventory used by the APCD seems to have been based on Cycle 4. This appears to have been the chief if not sole formal use so far of Cycle 4. Since Cycle 3 was not available for transportation modeling prior to the adoption in early 1974 of the JRPP transportation plan, it has never been formally agreed to by the JRPP or the DRCOG, acting as the JRPP Policy Body. The DRCOG, however, acting on its own, will ultimately use Cycle 4 for a revisiting of the JRPP transportation plan.

Water quality planning done pursuant to the 1972 Clean Water Act is required to address planning at the regional, basin and facilities level. The designation of these programs are 208 (regional), 303 (basin), and 201 (facilities). It appears that Cycle 4 population allocation forecasts were used for 208 program planning. Cycle 3, however, was used in the preparation of the Interim Regional Water Quality Management Plan.

Land use planning is intertwined with population level and allocation. The JRPP land plan, adopted in early 1974, underlies both Cycle 3 and Cycle 4 through specification of land availability and development parameters. The DRCOG, however, is undertaking a review of land use allocation, seeking a more specific restatement in light of new population allocation versions. It seems unlikely that such review will lead to a new land use plan in the time frame of this Overview EIS.

Transportation planning is subject to two additional uncertainties beyond population and land use considerations. The first includes the difficulties of forecasting the highway network at a particular time in the future. The second refers to the limitations of the transportation modeling process. In early 1974 the JRPP adopted a Year 2000 transportation plan. This plan became embedded in the transportation planning efforts conducted by both the DRCOG and the CDH. In the event that such a network proves substantially overbuilt and that the funding program necessary for its construction is an unrealistically ambitious one, RTD planning has been conducted using a more modest highway system referred to as the Existing plus Committed (E+C) network. Basically, it consists of those highway sections already built or for which funds have already been committed. Though RTD and CDH transportation planning both assume Cycle 3 population allocation, a basic inconsistency is introduced through their differing assumptions about highway network configuration.

As mentioned above transportation planning is also subject to uncertanties introduced through the limitations of transportation modeling. These models can be viewed in four segments: network configuration, trip generation, trip distribution and modal split (i.e., auto vs. rapid transit), and traffic assignment to highway links. Assumptions in any of these areas cascade through the modeling process, affecting the level and distribution of VMT projections. There have been three generations of transportation models in use by various agencies at different times. An idea of the magnitude of impact of changing modeling assumptions can be obtained by comparing total regional daily VMT projections in the year 2000. The second generation model projected a daily VMT of 38,000,000; the third generation model predicted about 30,000,000. This represents a 20 percent reduction in VMT due simply to changing behavioral assumptions about trip distribution and capacity restraint.

Transportation planning done by the DRCOG and the CDH was accomplished using second generation transportation models. Very recently, however, the DRCOG staff has been applying the third generation model using it in their efforts to revisit the JRPP transit plan. The RTD has also used the second generation model, although the trip table differs from the one used by the DRCOG/CDH because of their use of the E+C highway network rather than the JRPP plan. A transportation modeling run using the third generation model and the JRPP plan trip table does not appear to have been undertaken.

Underlying the above planning permutations are assumptions of fundamental importance in the planning process. A careful analysis of their impact on regional air quality requires an understanding of their basic form as well as detailed examination of the mutual consistency of agency plans. In order to further such understanding, the remainder of this section will be spent in detailing population (level and allocation), land use, and transportation (network configuration and modeling) planning.

b. Population Planning

Assumptions about growth, both as to its size and distribution, are central to the planning process. The projections that result serve as the basis for nearly all major planning decisions. As measures of the size, staging, and distribution of regional population, they determine the level of demand for urban services, such as highways, rapid transit, water services, and sewerage treatment. Growth in population provides the underlying justification for facilities construction or expansion.

It will be the purpose here to explore various aspects of the population forecasting and allocation process. Forecasts of population level will be explored first. Then the discussion will address the problem of allocating to the various communities the incremental gain in population due to growth.

1) Population Level

Recognizing its basic importance, the staff of the DRCOG has invested a sizable effort over the past five years in developing for the Metropolitan

Denver region a population level forecast through the year 2000. It is upon this forecast level of 2,350,000 that all subsequent planning in other agencies has been based.

Several forecasting techniques were considered as candidates by the DRCOG. Direct forecasts are based on historical data, such as fertility rates, birth and death rates, and in-migration levels. The method considers the annual growth in population to be the sum of two components, one proportional to the current level of population, i.e., the net of births over deaths, and the other equal to the net migration into the area.

Indirect forecasts usually relate population growth to other economic, social, and political indicators. Econometric methods are frequently used to relate past growth to several key explanatory indices, such as employment or personal income.

Summation of individual local forecasts is another method occasionally used. Such a method rarely maintains a regional perspective. Local communities tend to be optimistic when estimating their share of future growth, usually underplaying or ignoring the effects of competition from other communities for that same growth. As a result such forecasts tend to be higher than with other methods. The sum of local forecasts in the Denver region, for instance, originally totaled over 4,000,000 for the year 2000.

Saturation forecasting is still another method of projecting population. It is frequently applied by planning engineers to provide facilities designs sufficiently large to accomodate growth in the event it exceeds more realistic forecasts. Use of such methods is based on the assumption that it is less costly to overbuild initially than to extend capacity later in the event original forecasts prove conservative. In the past, however, these methods have led to overbuilding and underutilization of resources, as well as to inducing even higher growth than would otherwise have occurred.

After consideration of the above methods, the staff of the DRCOG chose the cohort-survival method, a direct forecasting technique. Cohort-survival decomposes growth into two components: (1) net natural increases, which is the net of births over deaths, and (2) the net of in-migration over out-migration. Assumptions are made concerning future birth/death rates and migration levels for each 5-year age group of the population. The method can in this way account for differences in the various age groups. Death rates, for example, would be much higher in the 65-70 age group than in those 30-35.

An application of the process can be outlined by the following steps, as indicated in Reference 17. First, the base year population, in 5-year age groups, is multiplied by the assumed death rates for each age group. These deaths are then subtracted from the base year population. Second, the net migrants for the time interval, by age group, are added to or subtracted from the surviving population. Finally, births are determined by considering males and females in the 15-44 age groups as potential parents. This population fraction is multiplied by an assumed birth rate for each age group, producing the expected number of births during the 5-year period. These births are then added to the surviving population and in-migrants to produce the total population at the end of the interval. Presumably, surviving members of each age group graduate to successive age groups as each iteration progresses.

It is clear from the above description that application of the cohort-survival forecasting technique embodies an extensive set of assumptions about the stratification of birth, death and migration variables. To simplify discussion, however, these can all be distilled down into two basic input variables: a single composite rate of net natural increase, and a single general in-migration level.

It was these two composite parameters that the DRCOG staff used as independent variables in preparing alternative population forecasts. The eight alternative cases considered in their analysis are outlined in Table C-7, from Reference 17, along with relevant assumptions and results.

TABLE C-7. DRCOG POPULATION FORECASTING ALTERNATIVES

ALTERNATIVE POPULATION FORECASTS

Case	Annual 1970-1980 Increase		Annual 1980-2000 Increase		Population (millions)		Simple 1970-2000 Growth Rate
	Net Natural	Migration	Net Natural	Migration	1980	2000	
I	Current Rate	1960's Level in 1975-80	Current Rate	1940-1970 Level	1.6	2.2	2.5%
II	Current Rate	Current Level	Current Rate	19[illegible]s Level	1.8	2.4	3.2%
III	Current Rage	Current Level	Current Rate	1960's Level Weighted by U.S. Pop.	1.8	2.5	3.5%
IV	Current Rate	Current Level	Current Rate	Current Level	1.8	3.0	4.9%
V	Current Rate	Current Level	Historical Rate	Current Level	1.8	3.3	5.5%
VI	Current Rate	Los Angeles 1943-1953	Current Rate	Los Angeles 1953-1970	2.0	3.9	7.2%
VII	Current Rate	Current Rate	Current Rate	Current Rate	1.8	4.3	8.4%
VIII	Declining to zero by 2050	1960's Level in 1975-80	Declining to zero by 2050	1940-1970 Level	1.6	2.1	2.4%

Net Natural: Current Rate (8.5/1,000 persons)
Historical (1900-1970) Rate (16.3/1,000 persons)

Migration: 1960's Level (15,700 persons)
1940-1970 Level (15,100 persons)
Current (1970-1973) Level (42,000 persons)
Current Rate (34/1,000 persons)

SOURCE: Denver Regional Council of Governments

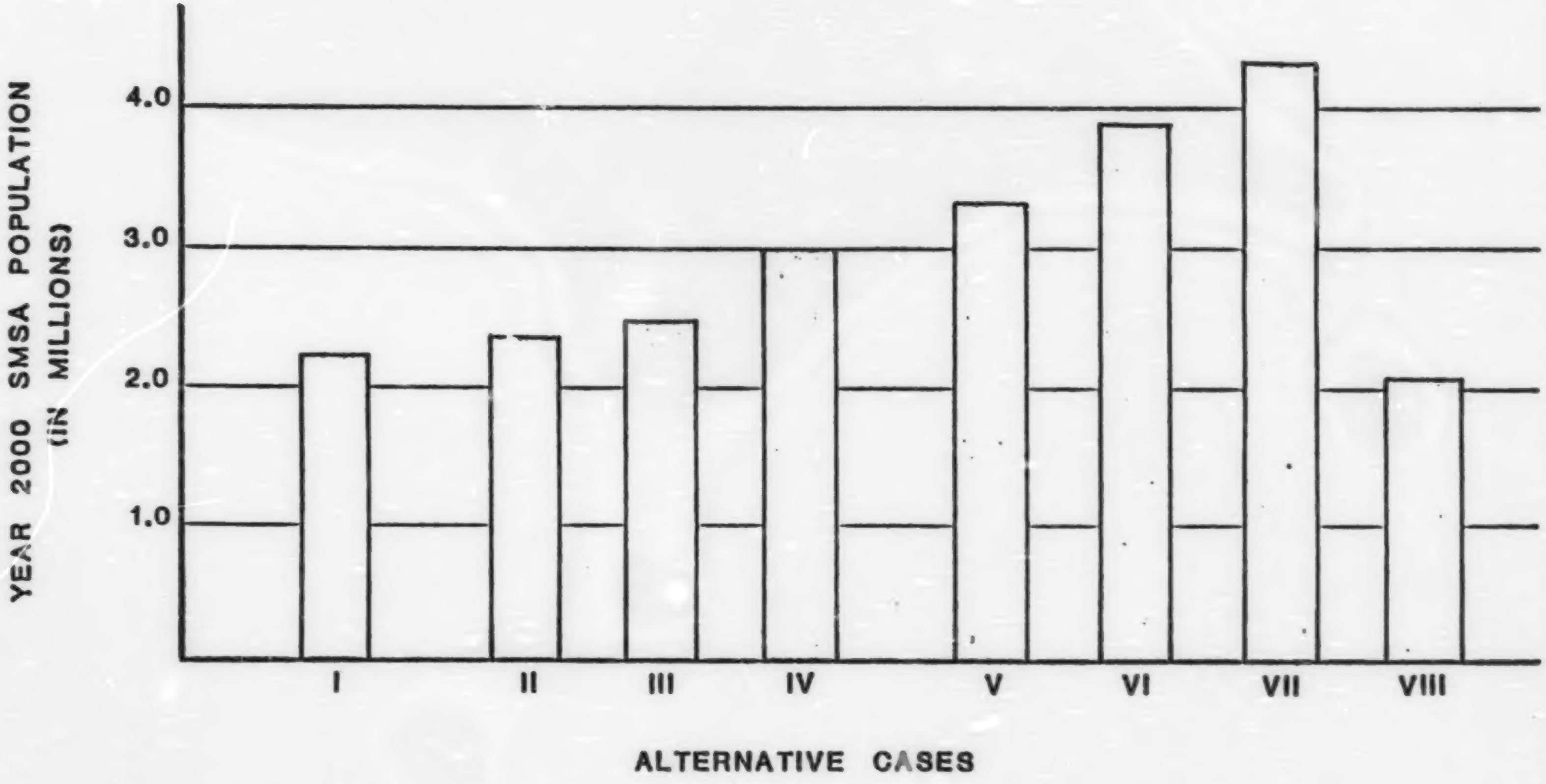
Alternative forecasts for the year 2000 are shown in Figure C-13, also from that reference.

Of these alternatives, Case I was chosen by the DRCOG to represent the baseline forecast. It assumes that the high level of migration experienced by the Denver region in the period 1971-73 will not continue through the year 2000, but that migration will approach the levels of the 1960's (15,700 annually) during 1975-1980 and the levels of the 30-year (1940-1970) average (15,100 annually) during 1980-2000. Case I also assumes that the net natural rate of population increase will continue at the 1972 rate (8.5 persons/1000 total population annually) through the year 2000.

These assumptions lead to a population forecast of 2,175,000 in the year 2000. Because of the sensitivity of this result to the above stated assumptions, it is instructional to compare the net natural increase rate and in-migration level with historical data available both before the 1972-73 study period and after (1973-1975). In Table C-8, the historical net natural increase rates are presented, with the birth and death rates shown graphically as in Figure C-14. Net migration levels are shown in Table C-9. All of these tables and the figure are from Reference 17.

Two interesting trends have exhibited themselves since the DRCOG study was done. First, as shown in Table C-8, the net natural increase rate declined from 8.5 per 1000 in 1972 to 6.3 per 1000 in 1974. This is consistent with a downward national trend in fertility rates. It is unclear, however, whether this is a true long-term phenomenon or simply a temporary dip due to the increasing trend of families towards later child-bearing. To the extent this is a true decline in birth rate, the DRCOG forecast may be proven to be high.

The second trend is the observed decrease in migration from the elevated levels of the early 1970's. From a high of 61,400 in 1972, migration into the Denver region has decreased. Although not noted in



SOURCE: DENVER REGIONAL COUNCIL OF GOVERNMENTS

FIGURE C-13. DRCOG ALTERNATIVE POPULATION FORECASTS FOR THE YEAR 2000

TABLE C-8. HISTORICAL NET NATURAL INCREASE RATES IN POPULATION

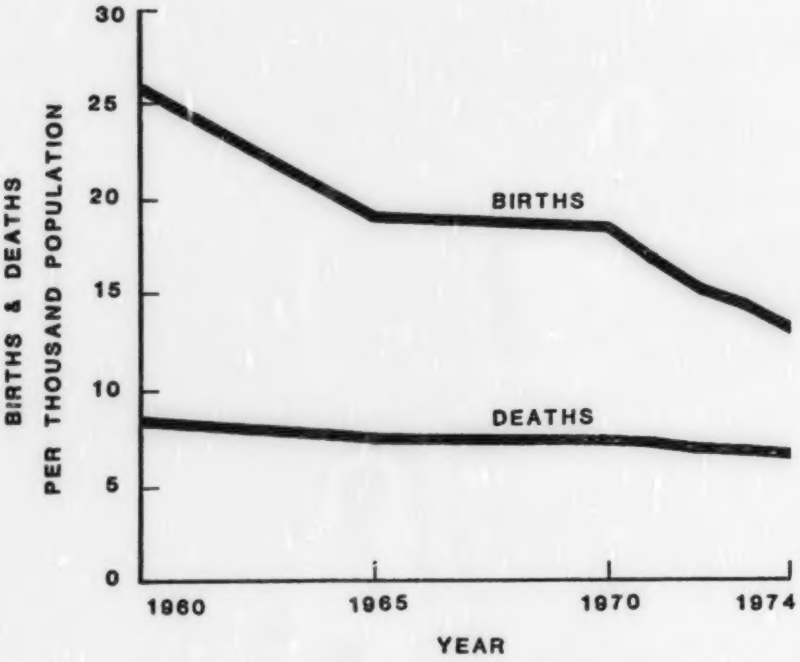
(rate per 1,000 population)

YEAR	DENVER REGION*	COLORADO	UNITED STATES
1960	17.2	15.8	14.1
1965	11.4	10.5	10.3
1970	11.0	10.9	8.9
1971	9.6	9.9	8.0
1972	8.5	8.6	5.7
1973	7.5	8.0	5.2
1974	6.3	7.1	4.7

---

* Rates for 1960 and 1965 are for the 5-county urbanized area, rates for 1970-74 are for the 8-county region.

SOURCES: Colorado Department of Health
U.S. Bureau of the Census
Denver Regional Council of Governments



NOTE: 1960 & 1965 FIGURES FOR 5-COUNTY URBAN AREA
1970-74 FIGURES FOR 8-COUNTY REGION

SOURCES: COLORADO STATE HEALTH DEPARTMENT
DENVER REGIONAL COUNCIL OF GOVERNMENTS

FIGURE C-14. HISTORICAL BIRTH AND DEATH RATES IN THE DENVER REGION

TABLE C-9. HISTORICAL NET MIGRATION IN THE DENVER REGION

PERIOD	AVERAGE ANNUAL IN-MIGRATION	RATE PER 1,000 POPULATION	PERCENT OF TOTAL POPULATION CHANGE
1940-1950	10,700	--	64%
1950-1960	18,800	--	59%
1960-1970	15,700	--	53%
1970-71	29,500	23.5	68%
1971-72	44,800	34.3	78%
1972-73	61,400	44.8	84%
1973-74	47,600	33.2	82%
1974-75	32,500	21.8	77%

SOURCE: Denver Regional Council of Governments

Table C-9, preliminary data for 1975-76 suggest that migration may have dropped as low as 16,000, much more in line with historical levels and the DRCOG staff assumptions in Case I. A determination of the permanence of this trend, however, is premature. More data are required to verify or refute Case I migration assumptions.

In order to approximate the sensitivity of Year 2000 population to changes in forecasting assumptions, the author developed the simplified forecasting analysis described in Annex C-1. According to that analysis, for Case I, a decrease in the rate of net natural increase of 1.0, e.g., from 8.5 per 1000 to 7.5, can be expected to decrease Year 2000 population by about 56,000. Similarly, an increase in the annual in-migration level of 1000 persons would lead to an increase in Year 2000 population of about 34,000.

In late 1972 the DRCOG staff recommended to the Council the adoption of Case I (2,175,000) as the accepted population forecast for planning purposes. The recommendation was initially reviewed and accepted. However, a period of extensive discussion ensued. By negotiation, another 175,000 (8 percent) was added to the recommeded Year 2000 total from Case I, giving a final total of 2,350,000. Most of the addition was attributed to the southeastern part of Jefferson County (southwest of Denver). By formal action on January 17, 1973, the Council of the DRCOG adopted the amended population forecast of 2,350,000.

The action of the Council in negotiating an addition of 175,000 to the staff-recommended Case I has created a change in the implied assumptions about migration. While Case I adhered well to historical levels, the migration level required to produce a Year 2000 population of 2,350,000 is about 22,000 person annually. This has been stated in several DRCOG publications (see References 17 and 18) and is confirmed by the author's analysis in Annex C-1. Critics have observed that such a level is appreciably higher than historical levels, except for those in the early 1970's. To assume so high a level (in historical terms) will persist over a 25 year period seems unrealistic, such critics have maintained. However, without tying migration to causal relationships, such as employment, income and other local economic indicators, the forecast of migration must be viewed as inherently speculative.

Without devoting too much space to the discussion, it is worth observing that other forecasts of population exist for the Metropolitan Denver region. Those totals for the year 2000 and the agencies responsible for them are presented in Table C-10 and shown graphically in Figure C-15, both from Reference 17.

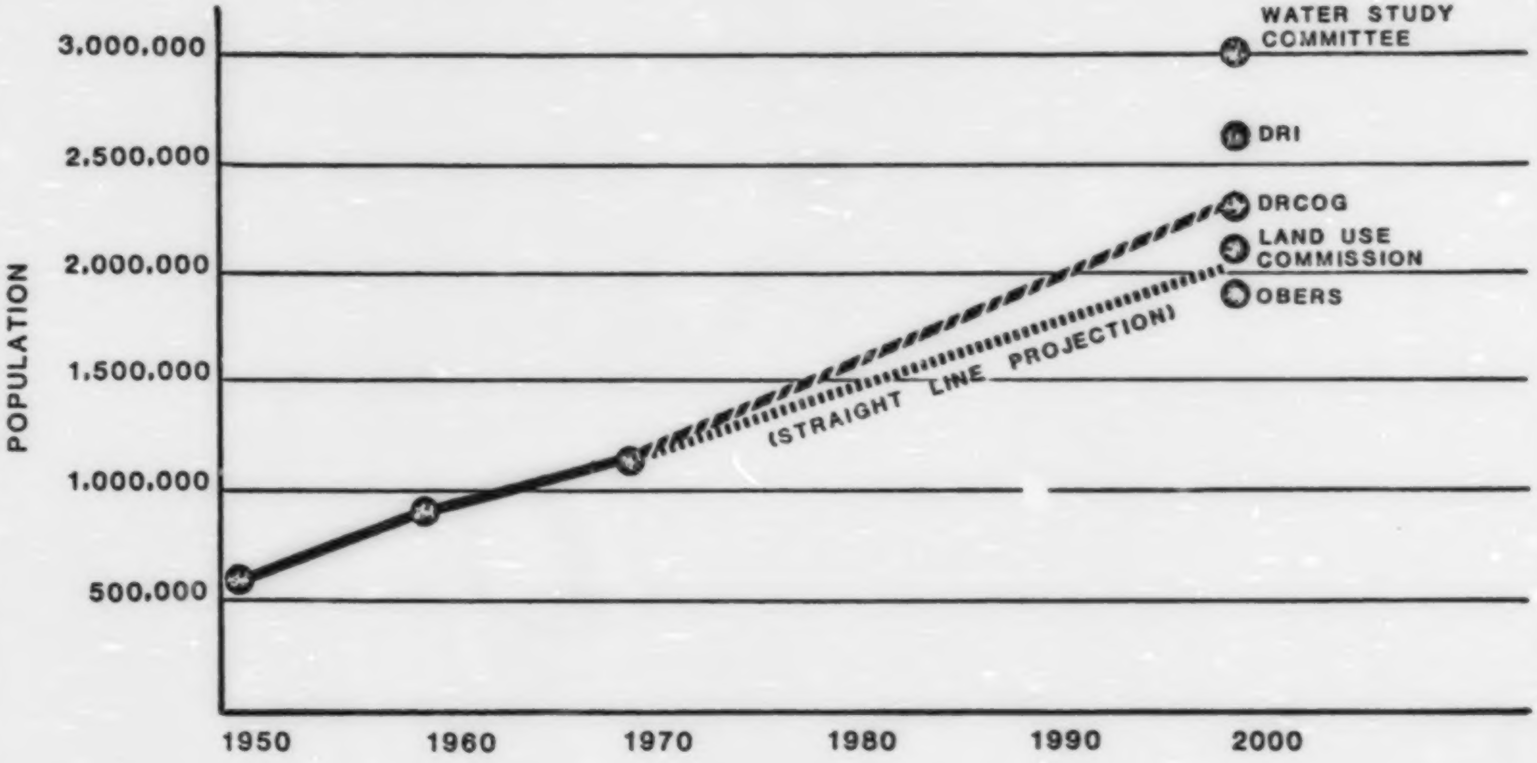
The OBERS projection seems to be the only one tied to economic indicators, assuming that migration will tend towards areas of economic opportunity and away from declining areas. It also is based on "Series E" projections of the national population, i.e., the total fertility rate (the total number of children a woman can be expected to have in her lifetime) will be 2.1 children. The chief criticism of the OBERS projection has been due to their assumption of saturation in migration, i.e., that the gradients in national economic forces that trigger migration will tend to even out over time.

As for the other studies, the Colorado Land Use Commission study done in 1972 simply relied on Case I projections. The 1975 Denver Research Institute study was based on a survey of the various population projections available at the time. DRI reasoned that a range of 2,350,000 to 3,000,000 was justifiable, accounting for uncertainties in the forecasting process. For convenience, they quoted the midpoint of that range as their expected projection. The Colorado Division of Planning projection was based on a 1974 survey of local government forecasts by county. Their result was simply the sum of the county totals. They also conducted a similar survey among municipal officials by city. They subsequently

TABLE C-10. ALTERNATIVE POPULATION FORECASTS FOR THE DENVER REGION IN THE YEAR 2000

1.	U.S. Commerce Department, Office of Business and Economic Research Service (OBERS)	1,981,000
2.	Colorado Land Use Commission	2,175,000
3.	DRCOG Policy Forecast	2,350,000
4.	Denver Research Institute (DRI)	2,675,000
5.	Colorado Division of Planning (County Total)	2,886,000
6.	Colorado Division of Planning (City Total)	2,892,000
7.	Metropolitan Denver Water Study Committee	3,000,000
8.	Colorado Division of Planning (Adjusted City Total)	3,399,000

SOURCES: Denver Regional Council of Governments
U.S. Department of Commerce
Colorado Land Use Commission
Denver Research Institute
Colorado Division of Planning
Metropolitan Denver Water Study Committee



SOURCE: DENVER REGIONAL COUNCIL OF GOVERNMENTS

FIGURE C-15. ALTERNATIVE PROJECTIONS OF POPULATION GROWTH FOR THE DENVER REGION issued an adjusted total forecast in which they substituted county forecasts when the sum of municipal projection was less than the county projection. The Metropolitan Denver Water Study Committee established in 1974 a projection of 3,000,000 based on the reasoning that an engineering safety factor was needed over the DRCOG-approved forecast. No other technical support for this choice seems to exist.

In summary while its embedded assumptions have at times been challenged, the DRCOG population forecast of 2,350,000 in the year 2000 is the Denver region planning standard by all practical terms. Whether its net natural increase rate and migration level are both too high must remain an unanswered question until current trends are either reinforced or refuted in the coming years.

2) Population Allocation

Even though the DRCOG has been able to agree on a population level for the Denver region, efforts at allocation of that population to individual communities have been subject to intense discussion. The lack of formal adoption of an allocation plan has not prevented the staff of the DRCOG from generating a series of iterations in population allocation, each subsequent version designed to account for deficiencies in the previous one. These allocation plans as they evolved became embedded in the plans of a number of other agencies, including the CDH, the RTD, and APCD.

In 1972 the EMPIRIC Activity Allocation Model was developed for the Denver region to assist in making these allocations. The model distributes to subareas of the region, by several subcategories, a wide range of characteristics, such as households, population and employment. This allocation is done by the simultaneous solution of a set of linear equations relating changes in population to changes in the characteristic indicators.

Of the iterations produced using EMPIRIC the last two applications, referred to as Cycle 3 and Cycle 4, have the most current relevance to the planning process. Those agencies using each of these have been noted earlier in this section. Since a number of differences exist in the policy scenarios examined by Cycle 3 and Cycle 4, it is instructive to outline the more important of these differences, as well as their similarities.

Direct policy inputs for both allocations were essentially the same. Both use the JRPP adopted Year 2000 highway and public transportation plans. Cycle 4 used an adjusted 1974 Metropolitan Water Study rather than the 1968 Study used in Cycle 3. A larger water service area was used in Cycle 4, and sewer service in Cycle 4 is based on the adopted Interim Regional Water Quality Plan which was only available in preliminary form when Cycle 3 was developed.

Indirect policy inputs vary considerably between Cycle 3 and Cycle 4. The DRCOG staff stated their desire to incorporate in Cycle 4 the eight adopted regional plan policys which were not available in the Cycle 3 application. For instance, while Year 2000 regional population totals 2,350,000 in both cycles, Cycle 4 did not specify the subregional controls that had been explicitly stated in Cycle 3 for county population equivalents. The concept of activity centers was more strongly implied in Cycle 4 through the use of direct minimum population and employment levels. Activity centers have represented in the planning process the focused concentration at a number of points in the Denver region of high levels of inward and outward movement, e.g., shopping centers, employment complexes, schools and universities, hospitals, to name just a few. Activity corridors, however, were not specified to the same degree in Cycle 4 as in Cycle 3. Policies for contiguous development, unique urban areas, and employment areas were developed by different means.

Land availability and development parameters were basically the same in both cycles. Land lying within 100-year floodplains or which has a slope greater than 15 percent was considered undevelopable. Remaining available space is assumed within EMPIRIC to be consumed at rates based upon "change densities," or the amount of land needed by increases in population. By decade planning districts are assigned to one of four types of development based on the extent of development in the initial, or base, year of the period. Densities are then applied to allocations of households to compute land consumption. In Cycle 3 it was assumed that half of all new development would be in single-family households while the remaining half would be in multi-family households. Cycle 4, however, assumed that 57 percent would be in single-family households with the remaining 43 percent in multi-family dwellings. The densities used to allocate population growth to land use consumption are presented in Table C-11, from Reference 18.

Based on the above listed variations in assumptions between Cycle 3 and Cycle 4, population allocation projections differed between the two. The extent of those differences are illustrated in Tables C-12 and C-13. A map of the county areas comprising the five-county Metropolitan Denver region is shown in Figure C-16. The above tables and figures are from Reference 18.

While both cycles have similar five-county population totals for all three forecast years, 1980, 1990 and 2000, there are substantial differences in the individual county figures, both in level and staging. Comparing Cycle 4 with Cycle 3, the principal differences in the year 2000 are slower growth in Denver and Jefferson counties with Cycle 4, with a compensating higher growth in Adams and Arapahoe counties. Also, in Cycle 4, almost no growth is projected to occur in Denver for the 1980-1990 period.

A third population allocation has been done for the Denver region. Referred to as the Subarea Allocation Plan, its importance in comparison with Cycle 3 and Cycle 4 is that the Council of the DRCOG on 18 August formally adopted it as DRCOG policy. Neither Cycle 3 nor Cycle 4 were ever formally adopted. It is important to recognize that the Subarea Allocation Plan (SAP), however, is not simply an iterative extension of

TABLE C-11. DENSITIES USED TO ALLOCATE GROWTH TO LAND CONSUMPTION

(dwelling units per net residential acre)

	Development Area			
Category	Core	Mature Developed Area	Rapidly Urbanizing Area	Satellite Area
Single-Family	7.0*	6.88	5.68	2.97
Multi-Family	53.6	31.40	19.40	7.89

*3/C EMPIRIC used 10.0 units/acre as a maximum.

TABLE C-12. PERCENT CHANGE IN POPULATION FOR EMPIRIC CYCLE 3 AND CYCLE 4

Geo-County	1970-1980		1980-1990		1990-2000	
	3/C	4/C	3/C	4/C	3/C	4/C
Adams	35.1	43.5	17.3	29.5	14.5	20.4
Arapahoe	61.0	73.0	30.8	37.4	20.3	29.5
Boulder	48.7	37.7	9.7	17.5	14.0	20.6
Denver	9.1	7.9	9.6	0.4	13.8	8.5
Jefferson	62.6	56.5	37.9	28.2	25.4	22.9
Total	34.2	34.2	20.6	19.3	18.1	19.4

TABLE C-13. COUNTY POPULATION ALLOCATIONS FOR EMPIRIC CYCLE 3 AND CYCLE 4

EMPIRIC County*	1980		1990		2000	
	3/C	4/C	3/C	4/C	3/C	4/C
Adams	251,000	266,600	294,400	345,300	337,200	415,600
Arapahoe	254,500	273,500	332,800	375,800	400,400	486,600
Boulder	196,000	181,500	215,000	213,300	245,000	257,200
Denver	565,500	559,300	619,700	561,500	705,200	609,000
Jefferson	383,000	368,800	528,100	472,800	662,200	581,300
Total	1,650,000	1,650,200	1,990,000	1,968,800	2,350,000	2,350,000

* Approximation of 1970 County jurisdictional area.

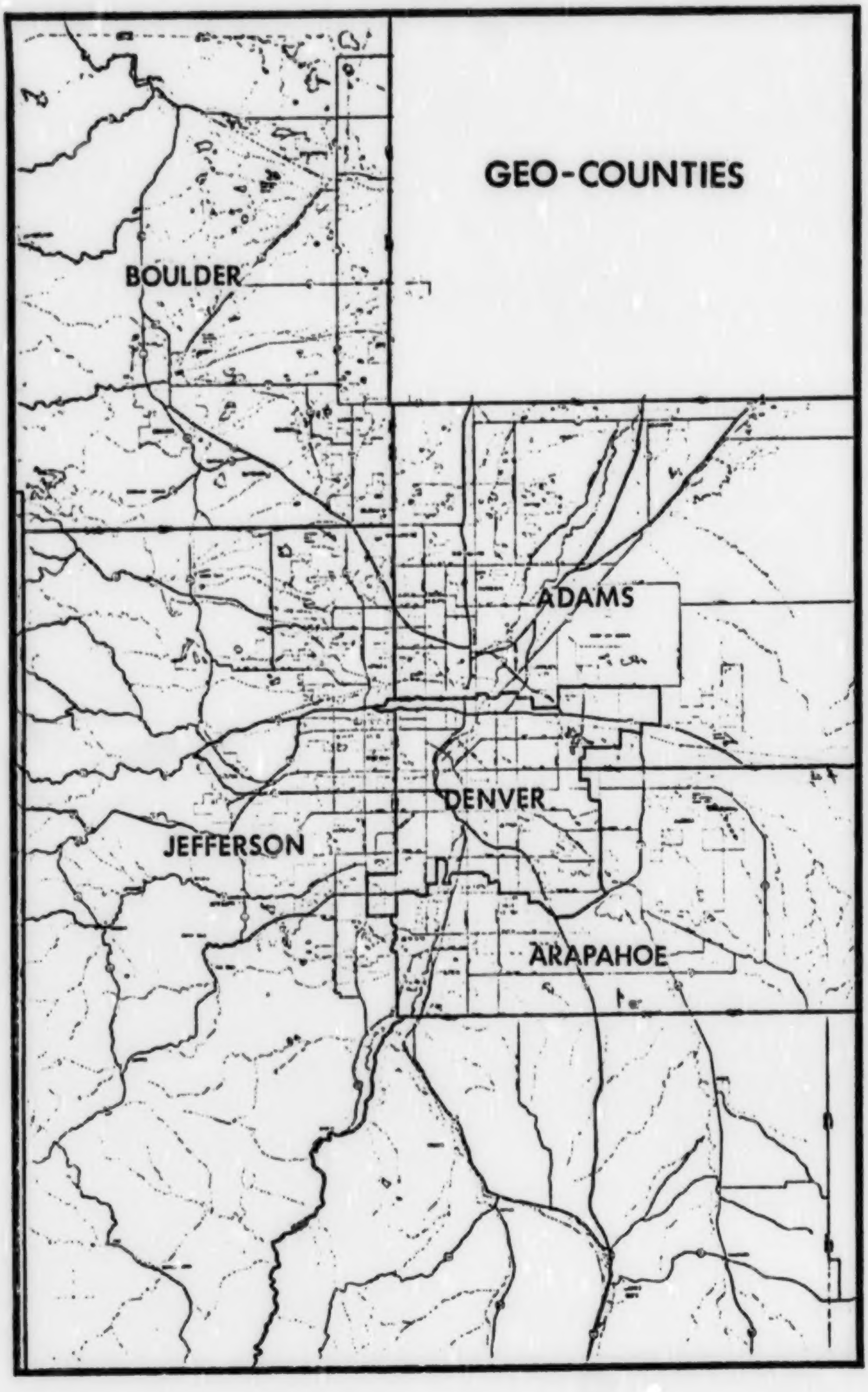

GEO-COUNTIES
BOULDER
ADAMS
DENVER
JEFFERSON
ARAPAHOE

FIGURE C-16. COUNTY AREAS IN DENVER REGION

Cycle 4. It is based much more directly on the local development plans proposed by each of the communities within the region.

The aggregate of the local plans totaled in the year 2000 to over 4,000,000 in the version first offered several years ago. In the time since the study was authorized in 1975, the DRCOG staff seems to have met with local planning staffs in an effort to evaluate the realism of their forecasts. Water supply and sewerage treatment capacity formed an important determinant of reasonability. After the completion of these discussions, the aggregate of local development plans had dropped to 2,739,200 in the year 2000.

Forecasting for the SAP was based on the concept of the Urban Service Area (USA). These are defined to be those parts of the region in which local governments plan to support urban development and redevelopment with urban services. In rough terms the boundaries of the USAs correspond to community boundaries as foreseen in the year 2000. Certain high growth areas not formally incorporated have also been defined as USAs. The division of the Denver region into USAs is shown in Figure C-17, from Reference 18.

Given the local development plans, the DRCOG staff still had to constrain the total Year 2000 regional population to the DRCOG-adopted level of 2,350,000. It was here that a major assumption was made. The staff assumed that although the sum of the local plans was too high by nearly 400,000 the relative percentages of the growth attributable to each community were in proper proportion. Based on this assumption, the local plans in each Urban Service Area were all scaled down by the same factor, one chosen to reduce the 2,739,200 total forecast to 2,350,000. Staging was kept the same as that forecast by the individual local development plans.

Those areas considered by DRCOG to be subject to relatively high growth rates are indicated in Figure C-18. In order to make more graphic the distribution and staging of these allocations, two series of regional

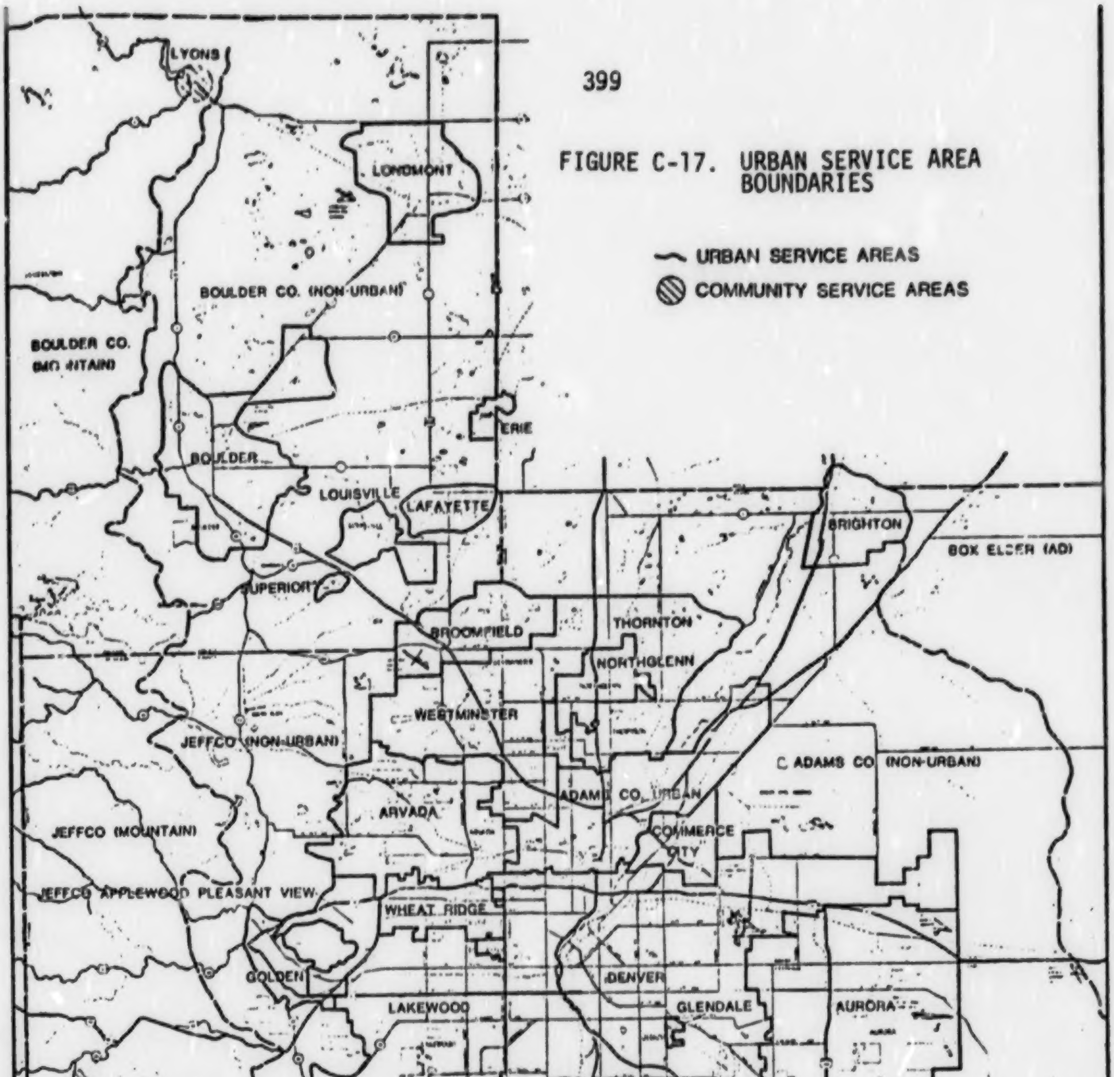

URBAN SERVICE AREAS
▨ COMMUNITY SERVICE AREAS
LYONS
LONGMONT
BOULDER CO. (NON-URBAN)
BOULDER CO. (MOUNTAIN)
ERIE
BOULDER
LOUISVILLE
LAFAYETTE
SUPERIOR
BRIGHTON
BOX ELDER (AD)
BROOMFIELD
THORNTON
NORTHGLENN
WESTMINSTER
JEFFCO (NON-URBAN)
ADAMS CO. (NON-URBAN)
ADAMS CO. URBAN
ARVADA
COMMERCE CITY
JEFFCO (MOUNTAIN)
JEFFCO APPLEWOOD PLEASANT VIEW
WHEAT RIDGE
GOLDEN
DENVER
LAKEWOOD
GLENDALE
AURORA
EVERGREEN
ENGLEWOOD
MORRISON
SHERIDAN
CHERRY HILLS VILLAGE
JEFFCO URBAN (S.E.)
LITTLETON
GREENWOOD VIL.
ARAPAHOE CO. URBAN
ARAPAHOE CO. (NON-URBAN)
DOUGLAS CO. URBAN
PARKER
DOUGLAS CO. (NON-URBAN)
SEDALIA
PINERY
ROXBOROUGH PARK
CASTLE ROCK

FIGURE C-17. URBAN SERVICE AREA BOUNDARIES

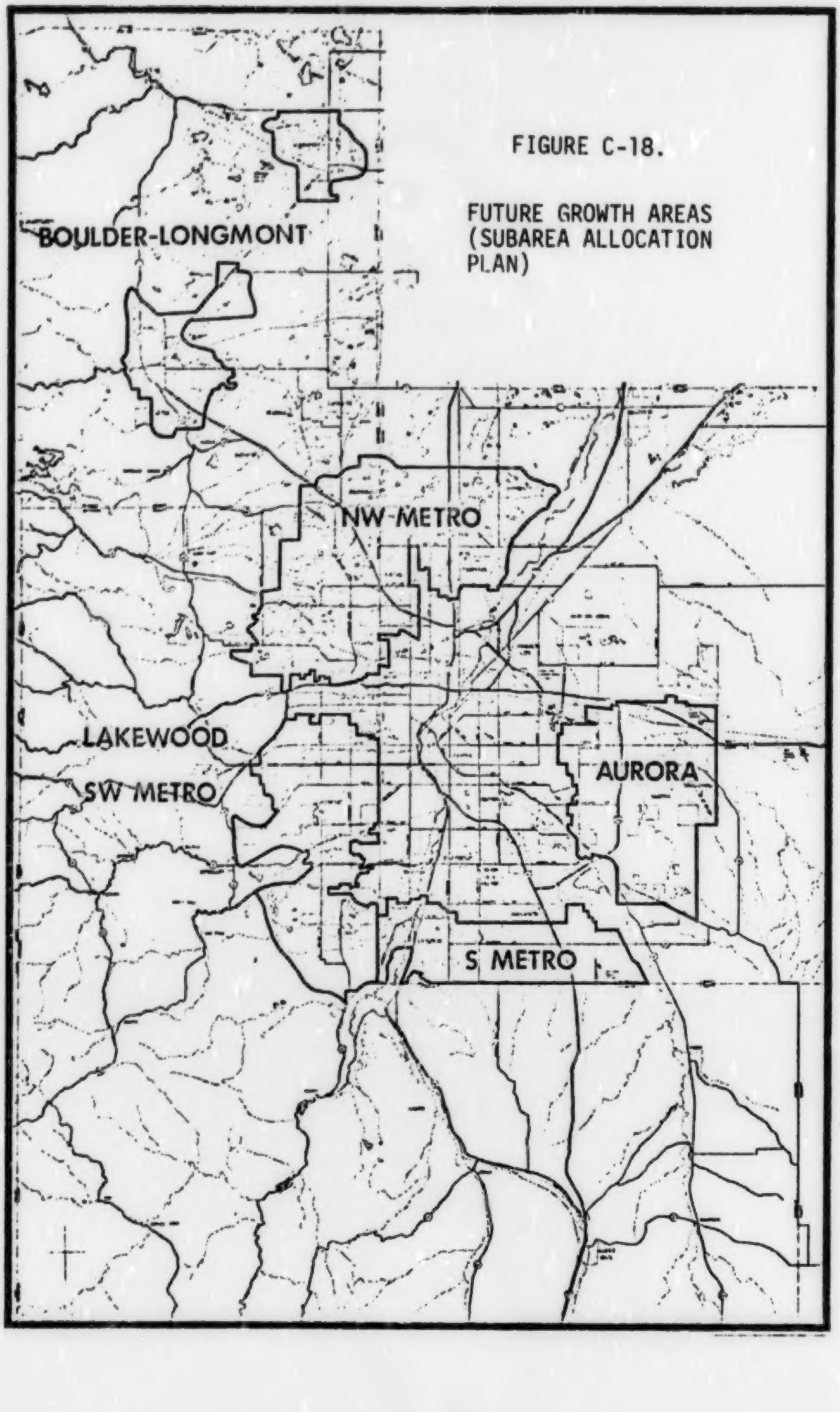

BOULDER-LONGMONT
NW METRO
LAKEWOOD
SW METRO
AURORA
S METRO

FIGURE C-18.

FUTURE GROWTH AREAS (SUBAREA ALLOCATION PLAN) maps are presented. In the first, Figures C-19(a) through C-19(e), the populations are shown at periodic intervals for each Urban Service Area in the Metropolitan Denver region. In the second series, Figures C-20(a) through C-20(e), subarea allocations by Urban Service Area in high growth areas are presented for consecutive time periods through the year 2000.

The issue of most basic interest to regional planners, however, is that of compatibility between the three current population allocation plans: Cycle 3, Cycle 4, and the Subarea Allocation Plan. The differences between the first two of these have been discussed earlier and are tabulated in Table C-13. The data in that table can be considered with the geo-county projections in Table C-14 to form a complete comparative set.

TABLE C-14. ALLOCATION PLAN COMPARISON (YEAR 2000)

Subarea	3/C	4/C	SPA
Adams	337,200	415,600	392,400
Arapahoe	400,400	486,600	418,700
Boulder	245,000	257,200	287,900
Denver	705,200	609,000	603,700
Jefferson	662,200	531,400	647,300
5 Co-Region	2,350,000	2,350,000	2,350,000

Notes: Subarea - Approximation of 1970 county jurisdiction
3/C - Third Cycle EMPIRIC Application
4/C - Fourth Cycle EMPIRIC Application
SPA - Subarea Population Allocation Study

A more detailed breakdown of the Subarea Allocation Plan by County and Urban Service Area are presented in Tables C-15 and C-16. The first two of these three tables are from Reference 18. The last table is from the text of Resolution No. 18, 1976, passed by the DRCOG (Reference 9).

The basic differences between the three projections are as follows. The Subarea Allocation Plan assigns to Denver a level in the year 2000 (603,700) slightly below the Cycle 4 allocation (609,000) and well below

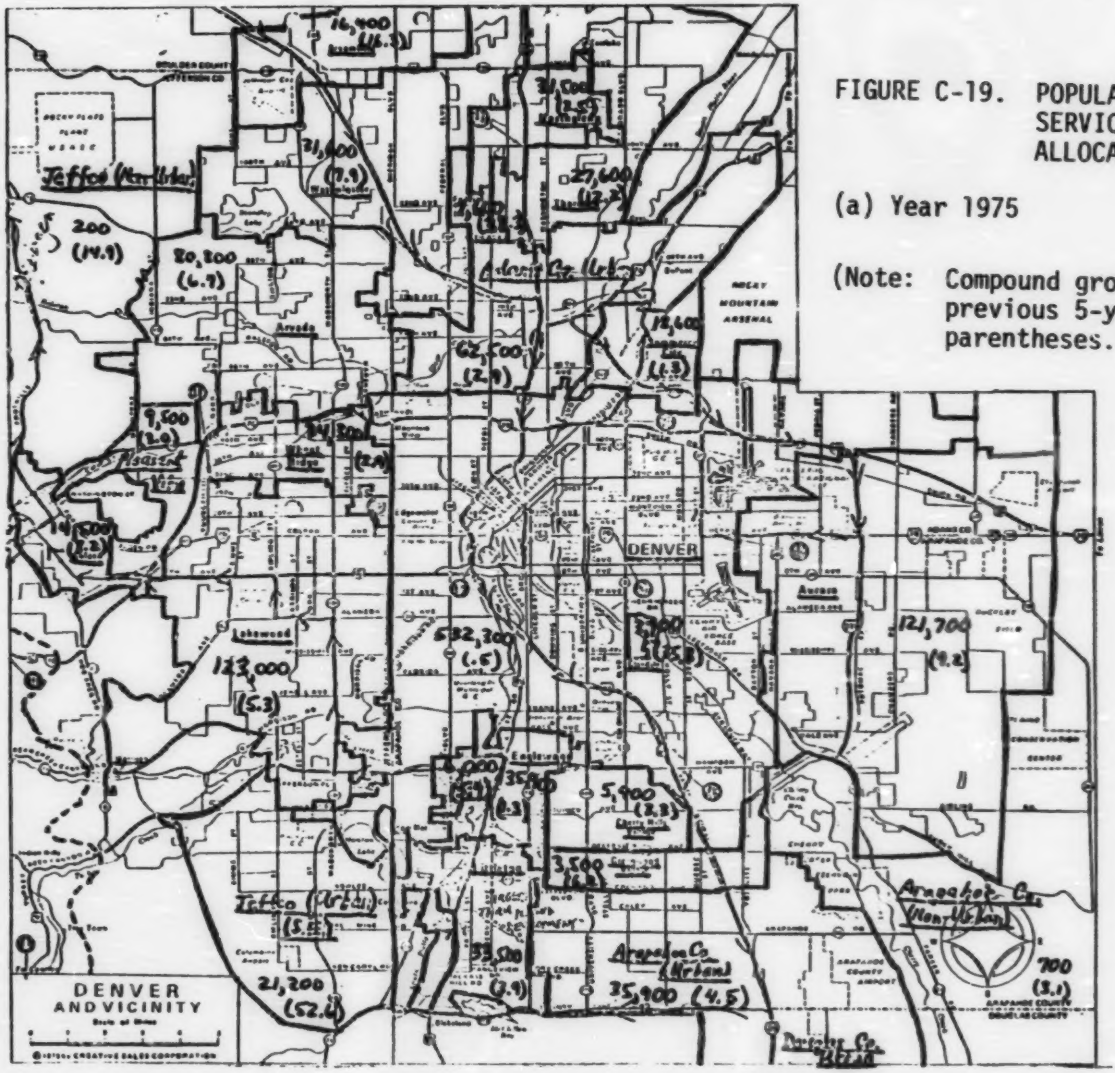

16,400
31,500
(2.5)
Jeffco (Non-Urban)
31,400
(7.9)
Westminster
27,600
(12.2)
Thornton
200
(14.9)
80,200
(6.9)
Adams Co. Urban
ROCKY MOUNTAIN ARSENAL
Arvada
18,600
(1.3)
62,500
(2.9)
9,500
(2.0)
34,800
(2.9)
Wheat Ridge
DENVER
Aurora
Lakewood
123,000
(5.3)
532,300
(.5)
121,700
(9.2)
Englewood
5,900
(2.3)
Cherry Hills
3,500
Littleton
Jeffco (Urban)
33,500
(3.9)
Arapahoe Co. (Urban)
35,900 (4.5)
Arapahoe Co. (Non-Urban)
700
(3.1)
21,200
(52.4)
Douglas Co.
DENVER AND VICINITY
ARAPAHOE COUNTY
DOUGLAS COUNTY
©1970 CREATIVE SALES CORPORATION

FIGURE C-19. POPULATION BY URBAN SERVICE AREA (SUBAREA ALLOCATION PLAN)

(a) Year 1975

(Note: Compound growth rates over previous 5-years are in parentheses.)

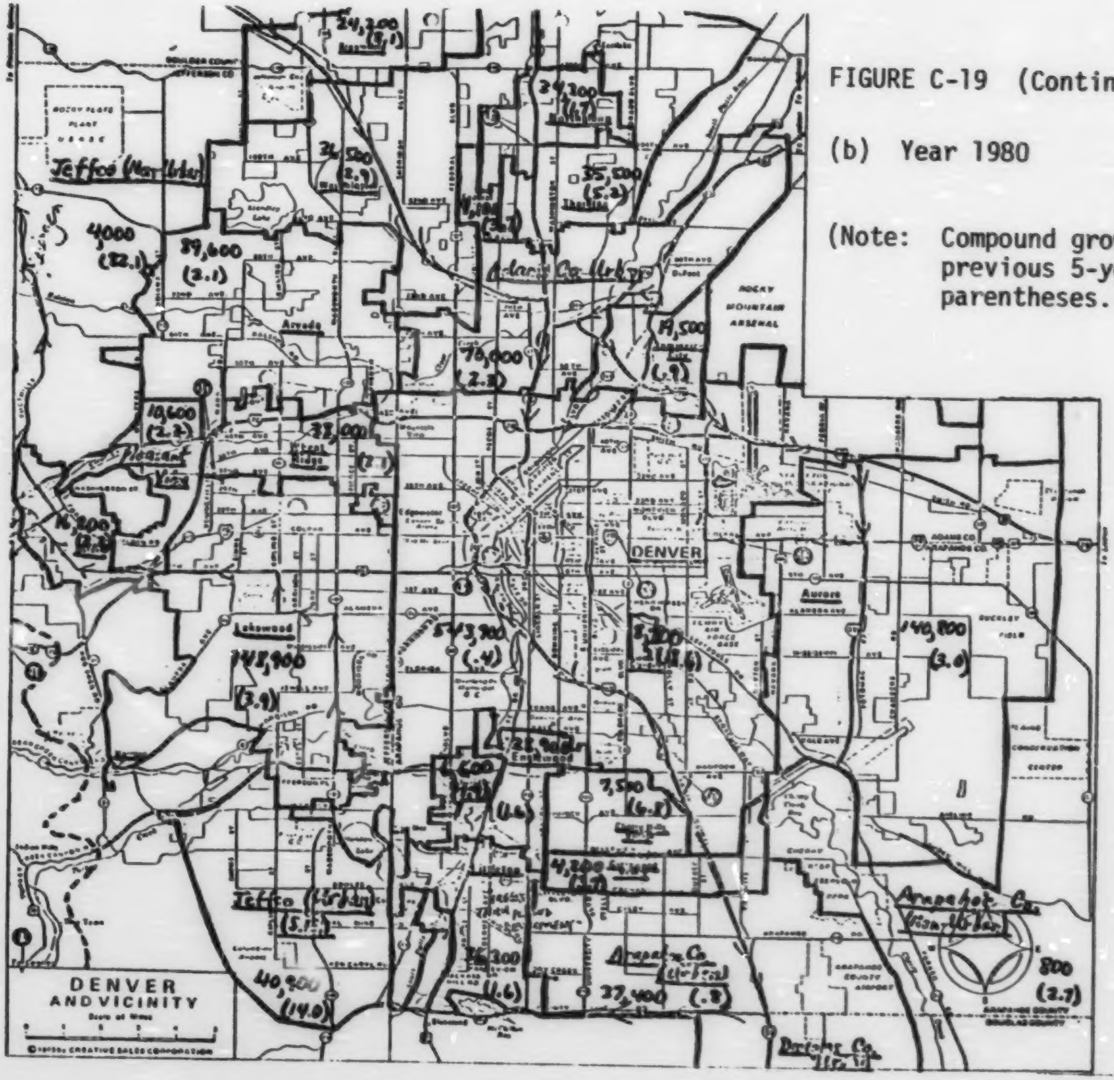

24,200
(9.1)
Jeffco (Non-Urban)
4000
(22.1)
31,500
(2.9)
Westminster
39,600
(2.1)
Arvada
34,300
(4.7)
Northglenn
35,500
(5.2)
Thornton
Adams Co. Urban
76,000
(2.3)
19,500
Commerce City
(.9)
ROCKY MOUNTAIN ARSENAL
10,600
(2.2)
33,000
Wheat Ridge
(2.1)
Pleasant View
16,300
(2.3)
DENVER
543,300
(.4)
Aurora
140,800
(3.0)
Lakewood
147,900
(3.9)
28,900
Englewood
7,590
(6.8)
4,200
(2.0)
Jeffco (Urban)
(5.1)
Littleton
36,300
(1.6)
40,900
(14.0)
Arapahoe Co. (Urban)
37,400
(.8)
Arapahoe Co. Non-Urban
800
(2.7)
Douglas Co.
DENVER AND VICINITY
Scale of Miles
©1970 CREATIVE SALES CORPORATION

FIGURE C-19 (Continued)

(b) Year 1980

(Note: Compound growth rates over previous 5-years are in parentheses.)

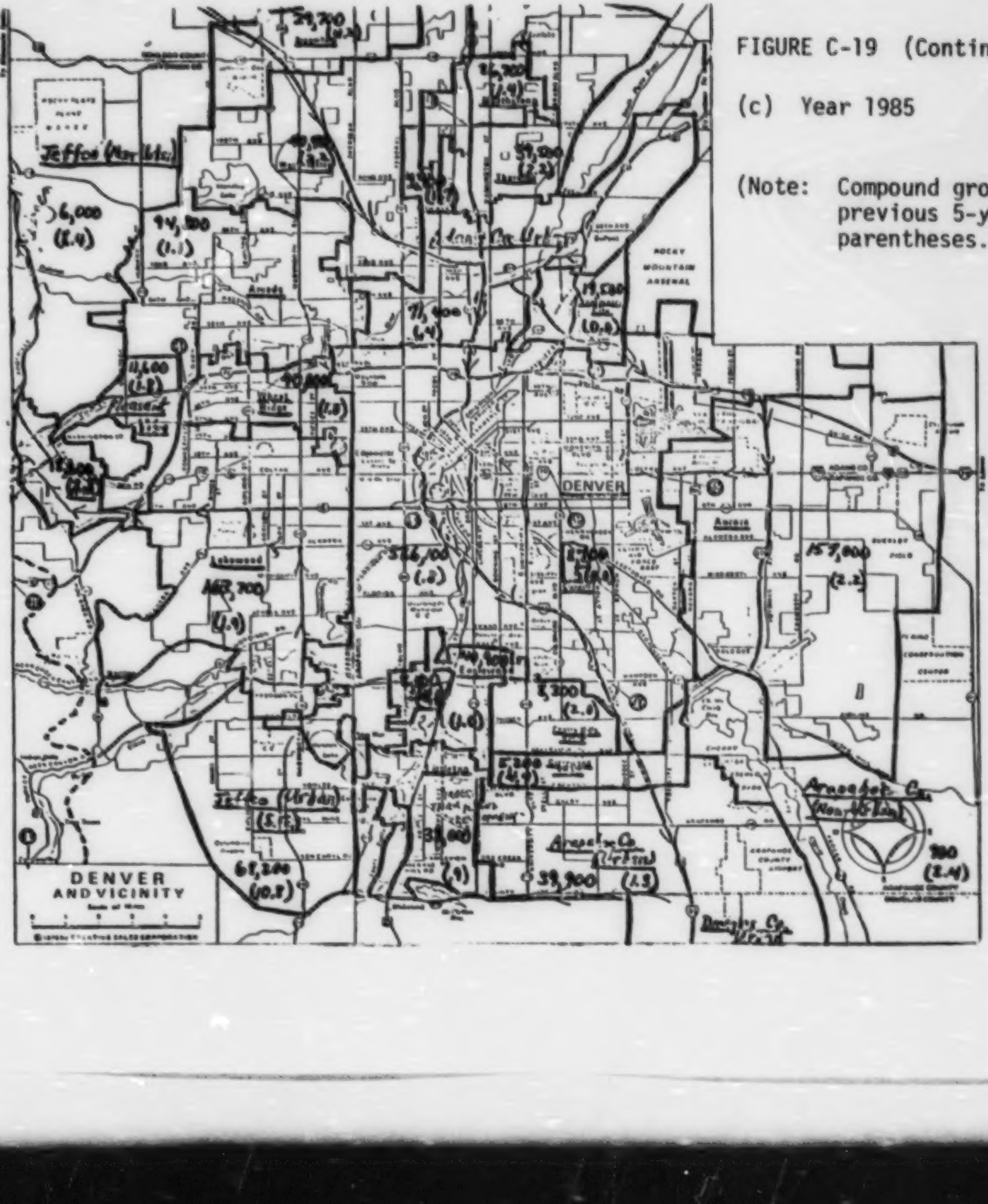

29,700
(4.3)
26,700
(1.9)
Jeffco (Non Urb)
39,200
(2.2)
6,000
(2.4)
94,500
(1.1)
Adams Co. Urb
ROCKY MOUNTAIN ARSENAL
Arvada
71,400
(.4)
19,580
(0.8)
11,600
(1.8)
90,800
Wheat Ridge
(1.8)
Golden
17,300
(2.3)
DENVER
Aurora
Lakewood
566,100
(.2)
2,700
5(0.0)
157,000
(2.2)
162,700
(1.9)
Englewood
5,300
(2.0)
(1.0)
Jeffco (Urban)
(5.18)
5,200
(4.9)
Arapahoe Co. (Non Urban)
38,000
Arapahoe Co. (Urban)
67,200
(10.8)
(.1)
39,900
(1.3)
780
(2.4)
Douglas Co.
DENVER
AND VICINITY

FIGURE C-19 (Continued)

(c) Year 1985

(Note: Compound growth rates over previous 5-years are in parentheses.)

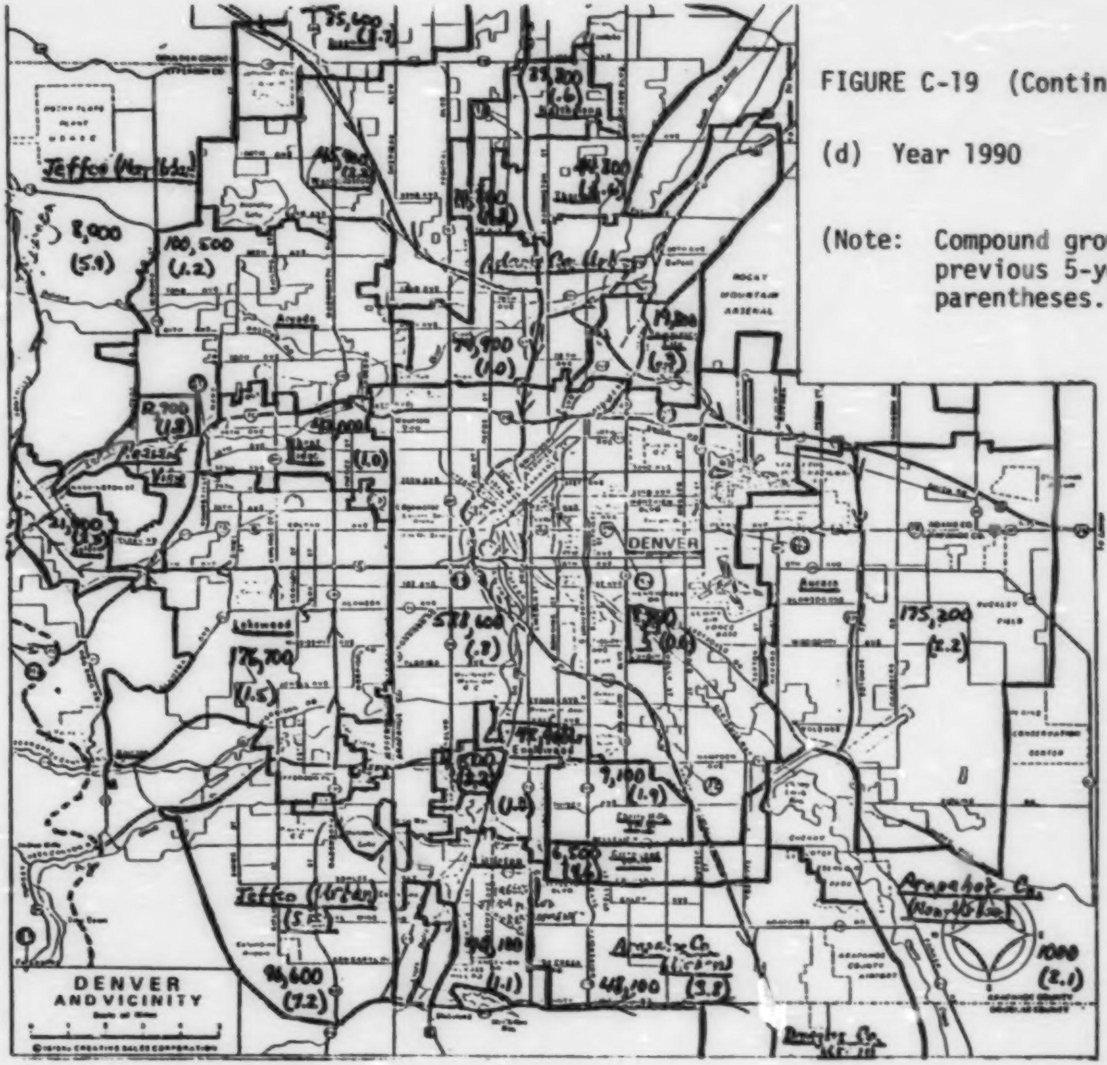

35,600
(1.7)
35,200
(.6)
Jeffco (Non-Urban)
145,900
(1.2)
40,200
(1.6)
8,000
(5.9)
100,500
(1.2)
Adams Co. Urban
ROCKY MOUNTAIN ARSENAL
Arvada
19,200
(.3)
79,900
(1.0)
12,700
(1.3)
Pleasant View
(1.0)
21,700
(3.3)
DENVER
Aurora
578,600
(.8)
175,200
(2.2)
Lakewood
175,700
(1.5)
Englewood
7,100
(1.9)
Cherry Hills Village
6,500
(4.6)
Jeffco (Urban)
(5.2)
Arapahoe Co.
(Non-Urban)
1000
(2.1)
48,100
(5.8)
96,600
(7.2)
(1.1)
Douglas Co.
DENVER
AND VICINITY

FIGURE C-19 (Continued)

(d) Year 1990

(Note: Compound growth rates over previous 5-years are in parentheses.)

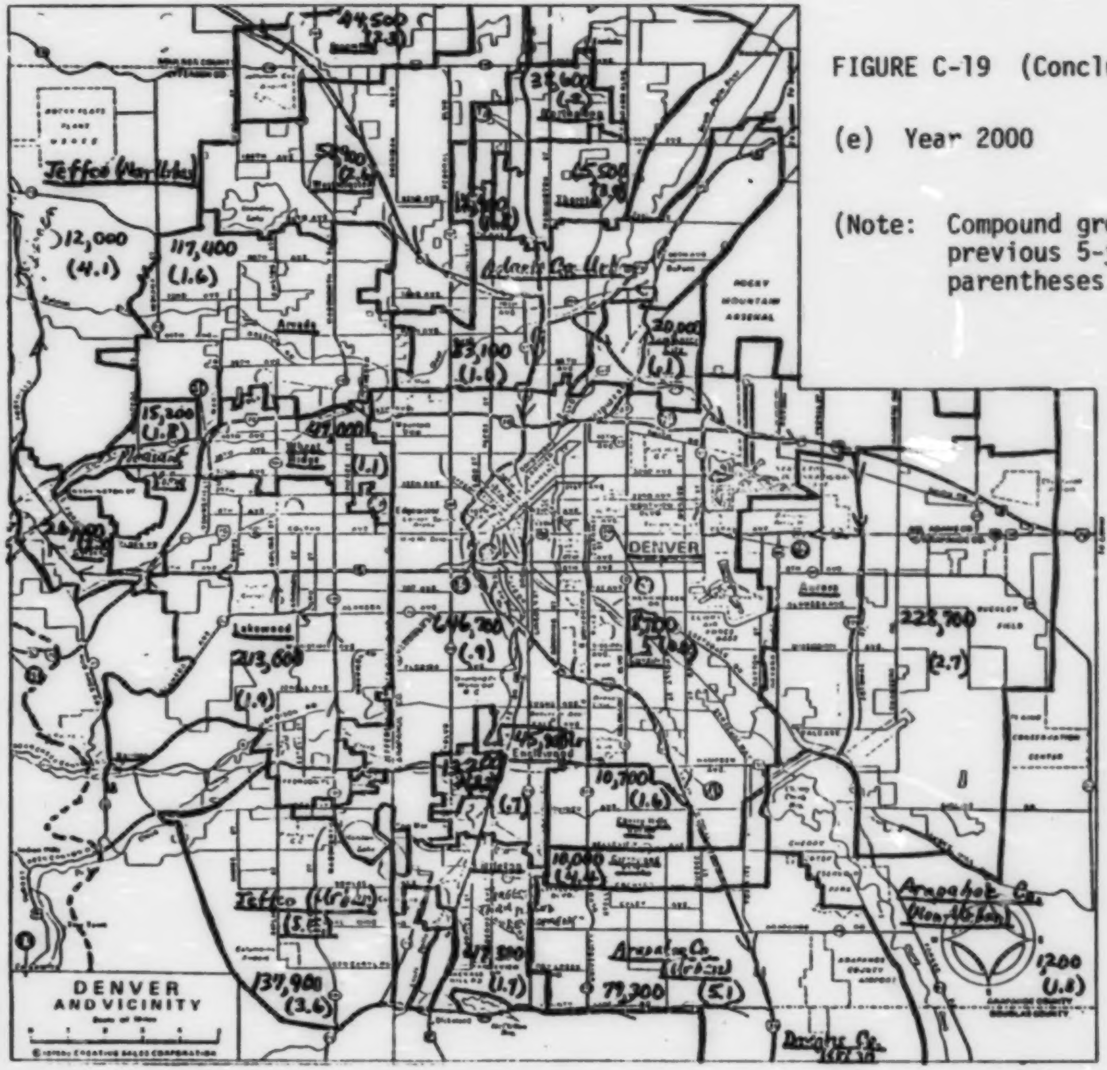
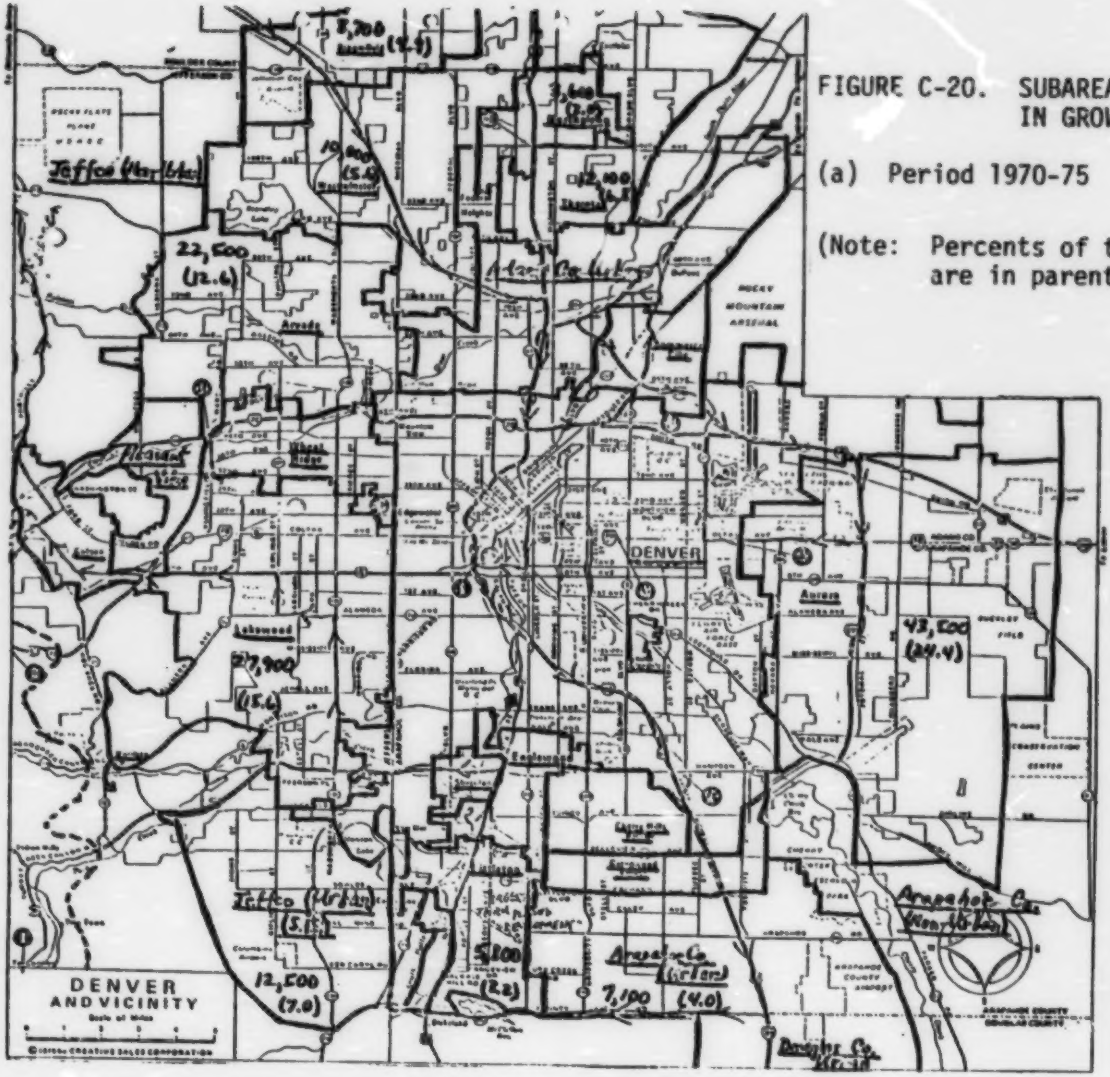

44,500
(2.3)
Jeffco (Non-Urban)
)12,000
(4.1)
117,400
(1.6)
53,900
(2.4)
33,600
(.2)
45,500
(3.0)
Adams Co. Urban
ROCKY
MOUNTAIN
ARSENAL
20,000
(.1)
33,100
(1.0)
Arvada
15,200
(1.8)
47,000
Wheat
Ridge
(1.1)
DENVER
Aurora
Lakewood
213,600
(1.9)
616,700
(.9)
228,700
(2.7)
45,900
Englewood
10,700
(1.6)
13,200
(.7)
10,000
(4.4)
Jeffco (Urban)
(5.8)
Arapahoe Co.
(Non-Urban)
Arapahoe Co.
(Urban)
79,300
(5.1)
47,300
(1.7)
137,900
(3.6)
1,200
(0.8)
Douglas Co.
DENVER
AND VICINITY

FIGURE C-19 (Concluded)

(e) Year 2000

(Note: Compound growth rates over previous 5-years are in parentheses.)



8,700
(4.9)
3,600
(2.0)
10,900
(5.6)
Westminster
12,100
(6.8)
Thornton
Jeffco (Non-Urban)
22,500
(12.6)
Adams Co. (Urban)
Arvada
Wheat Ridge
DENVER
Aurora
Lakewood
27,900
(15.6)
43,500
(24.4)
Englewood
Littleton
Jeffco (Urban)
(5.1)
5,100
(2.2)
12,500
(7.0)
Arapahoe Co. (Urban)
7,100
(4.0)
Arapahoe Co. (Non-Urban)
Douglas Co.
ROCKY MOUNTAIN ARSENAL
DENVER AND VICINITY
Scale of Miles
©1970 CREATIVE SALES CORPORATION

FIGURE C-20. SUBAREA ALLOCATIONS OF POPULATION IN GROWTH AREAS BY TIME PERIOD

(a) Period 1970-75

(Note: Percents of total regional allocation are in parentheses.)

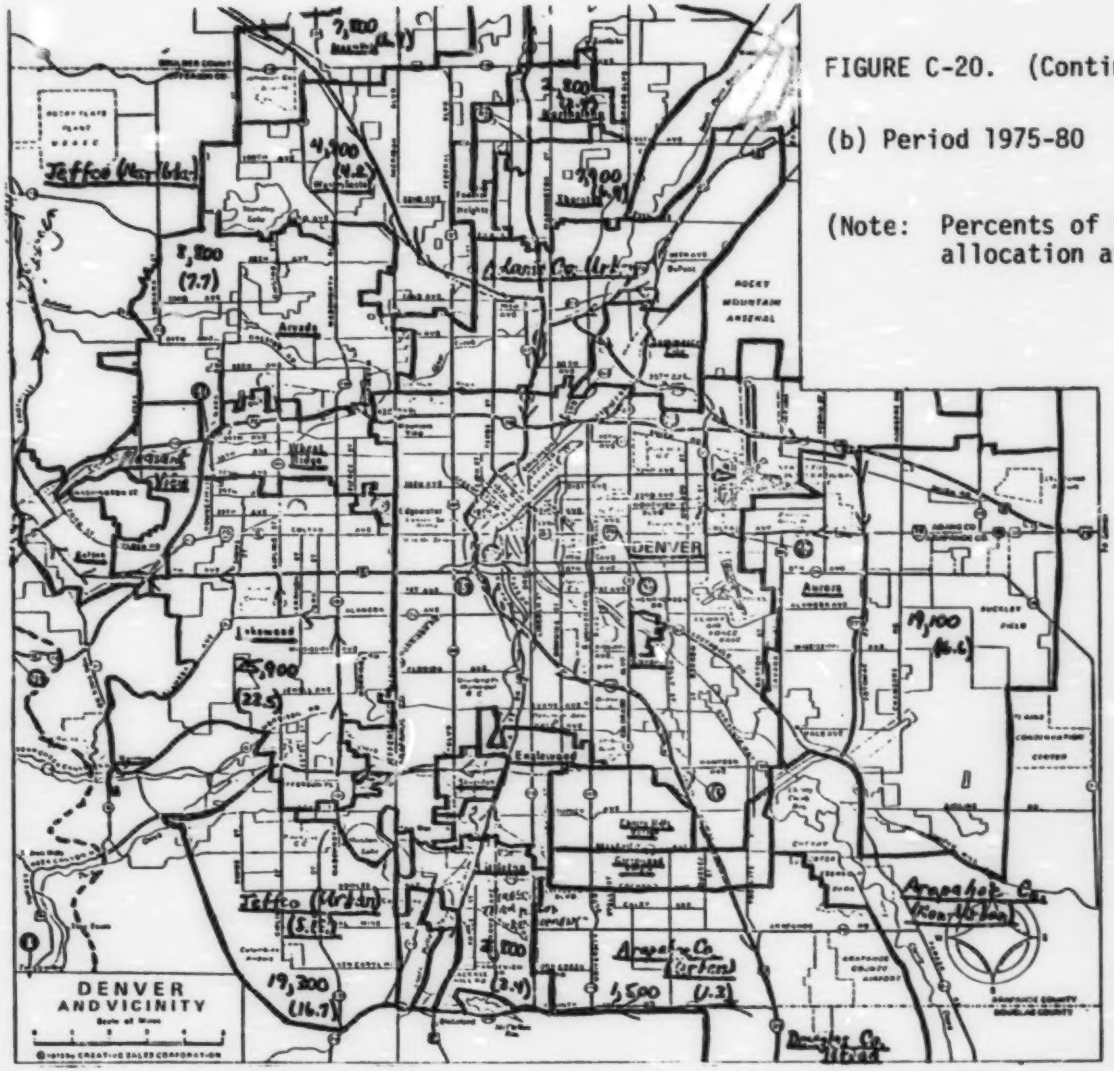

7,800
Jeffco (Non-Urban)
4,900
(4.2)
Westminster
2,800
Northglenn
7,900
Thornton
8,800
(7.7)
Arvada
Adams Co. Urban
ROCKY MOUNTAIN ARSENAL
Wheat Ridge
Lakewood
25,900
(22.5)
DENVER
Aurora
19,100
(16.6)
Englewood
Cherry Hills Village
Jeffco (Urban)
(5.8)
19,300
(16.7)
2,800
(2.4)
Arapahoe Co. (Urban)
1,500
(1.3)
Arapahoe Co. (Non-Urban)
Douglas Co.
DENVER AND VICINITY

FIGURE C-20. (Continued)

(b) Period 1975-80

(Note: Percents of total regional allocation are in parentheses.)

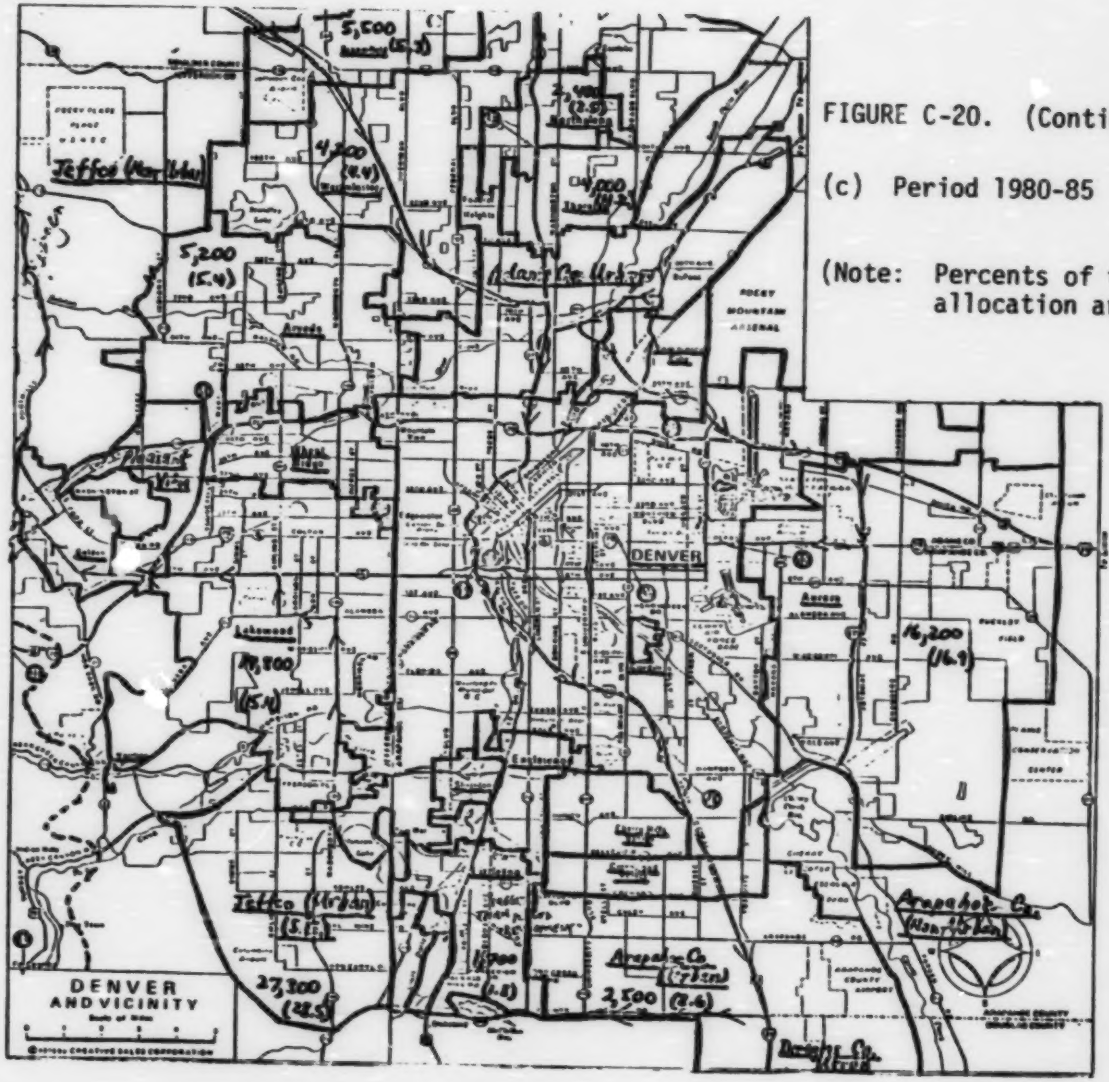

5,500
(5.3)
2,400
(2.5)
Northglenn
4,200
(4.4)
Westminster
4,000
(4.2)
Thornton
Jeffco (Non-Urban)
5,200
(5.4)
Adams Co. Urban
ROCKY MOUNTAIN ARSENAL
Arvada
Wheat Ridge
Pleasant View
DENVER
Lakewood
14,800
(15.4)
Aurora
16,200
(16.9)
Englewood
Jeffco (Urban)
(5.1)
27,300
(28.5)
(1.8)
Arapahoe Co.
(Urban)
2,500
(2.6)
Arapahoe Co.
(Non-Urban)
Douglas Co.
DENVER
AND VICINITY

FIGURE C-20. (Continued)

(c) Period 1980-85

(Note: Percents of total regional allocation are in parentheses.)

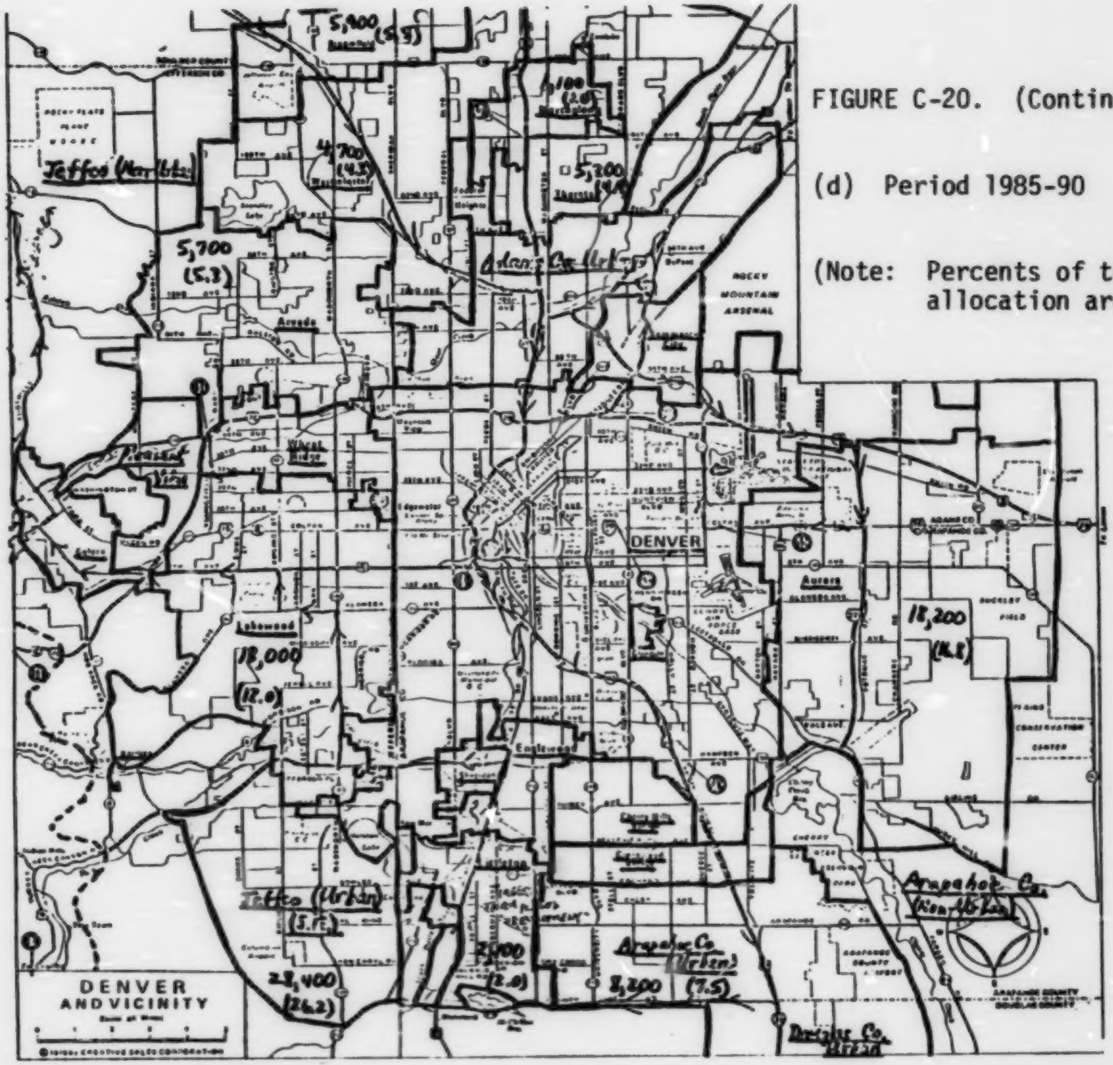

5,900 (5.5)
2,100 (2.0)
Jeffco (Non-Urban)
4,700 (4.3)
5,200 (4.8)
5,700 (5.3)
Adams Co. Urban
ROCKY MOUNTAIN ARSENAL
ROCKY FLATS PLANT
Arvada
Wheat Ridge
DENVER
Aurora
Lakewood
18,000 (17.0)
18,200 (16.8)
BUCKLEY FIELD
Englewood
Jeffco (Urban)
(5.8)
28,400 (26.2)
2,100 (2.0)
Arapahoe Co. (Urban)
8,200 (7.5)
Arapahoe Co. (Non-Urban)
Douglas Co.
DENVER AND VICINITY

FIGURE C-20. (Continued)

(d) Period 1985-90

(Note: Percents of total regional allocation are in parentheses.)

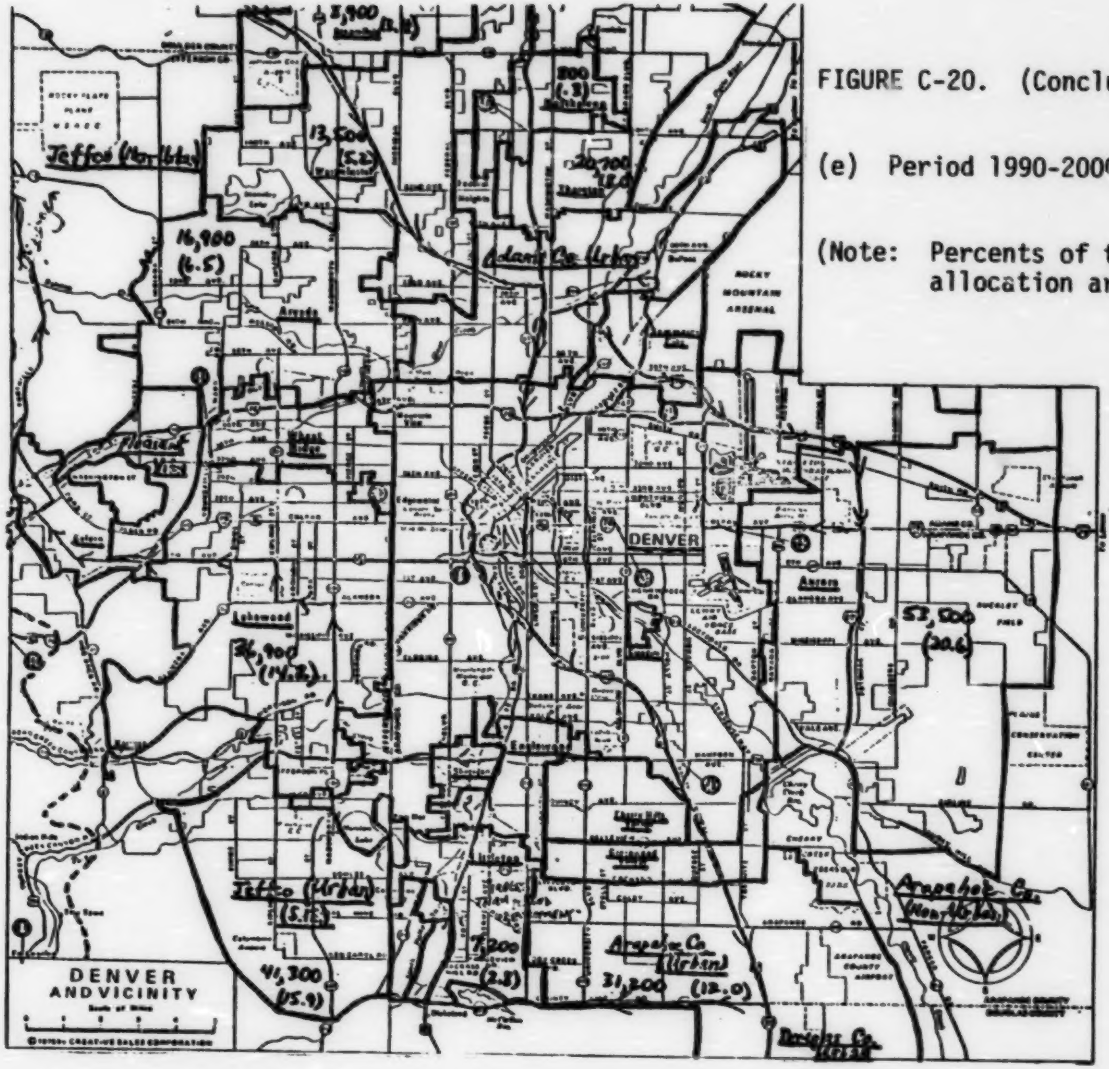

3,900
(1.5)
Jeffco (Non-Urban)
13,500
(5.2)
800
(.3)
20,700
(8.0)
16,900
(6.5)
Adams Co. Urban
ROCKY MOUNTAIN ARSENAL
DENVER
Lakewood
36,900
(14.2)
Aurora
53,500
(20.6)
Englewood
Jeffco (Urban)
(5.1)
7,200
(2.8)
41,300
(15.9)
Arapahoe Co. (Urban)
31,200
(12.0)
Arapahoe Co. (Non-Urban)
Douglas Co.
DENVER AND VICINITY

FIGURE C-20. (Concluded)

(e) Period 1990-2000

(Note: Percents of total regional allocation are in parentheses.)

TABLE C-15. SUBAREA ALLOCATION PLAN BY COUNTY (1970-2000)

County	Base	Current	Short Term			Long Term
	1970	1975	1980	1985	1990	2000
Jurisdictional*						
Adams	185,800	230,700	767,400	288,800	308,300	360,800
Arapahoe	162,100	223,400	254,700	278,900	313,600	420,300
Boulder	131,900	169,900	194,100	217,000	244,500	286,400
Jefferson	235,300	322,700	395,100	456,300	518,000	625,600
	715,100	944,500	1,111,300	1,241,000	1,384,400	1,693,100
Denver	514,700	527,100	538,900	561,500	584,400	656,900
Region	1,229,800	1,473,800	1,650,200	1,802,500	1,968,800	2,350,000
Geo-County**						
Adams	185,800	230,700	267,400	294,400	319,500	392,400
Arapahoe	158,100	219,400	247,700	274,200	310,900	418,700
Boulder	131,900	169,900	193,600	217,400	245,900	287,900
Jefferson	235,600	323,400	397,100	459,000	521,600	647,300
	711,400	943,400	1,105,800	1,245,000	1,397,900	1,746,300
Denver	518,400	530,400	544,400	557,500	570,900	603,700
Region	1,229,800	1,473,800	1,650,200	1,802,500	1,968,800	2,350,000

* Current jurisdictional area.

** Aggregation of Transportation Study Districts approximating 1970 county jurisdictional area.

TABLE C-16. SUBAREA ALLOCATION PLAN BY SERVICE AREA (1970-2000)

Service Area	Base	Current	Short Term			Long Term
	1970	1975	1980	1985	1990	2000
Mountain	24,800	29,600	34,600	40,000	46,600	55,500
Boulder Co Mtn	5,700	5,900	6,600	6,700	6,700	7,900
Evergreen*	5,700	7,800	9,900	12,000	14,000	16,800
Jefferson Co Mtn.	11,900	14,200	16,900	18,700	22,500	26,800
Lyons*	1,000	1,000	1,300	1,600	2,000	2,500
Nederland*	500	700	900	1,100	1,400	1,500
Plains	4,000	4,400	5,800	6,800	7,800	9,900
Bennett*	700	900	1,400	1,700	2,000	2,300
Box Elder (Ad)	400	400	600	700	900	1,100
Box Elder (Ar)	400	400	500	500	500	600
Byers*	400	400	500	700	800	1,000
Deer Trail*	400	400	400	400	400	400
East Plains (Ad)	100	200	800	600	300	100
East Plains (Ar)	600	700	600	700	900	1,400
Strasburg*	1,000	1,000	1,000	1,500	2,000	3,000

*Community Service Area

TABLE C-16 (Continued)

Service Area	Base	Current	Short Term			Long Term
	1970	1975	1980	1985	1990	2000
Valley	1,201,000	1,439,800	1,609,800	1,755,700	1,914,400	2,284,600
Adams Co (Uninc)	9,600	10,500	12,000	14,200	14,400	14,800
Adams Co (Urban)	54,200	62,500	70,000	71,400	74,900	83,100
Arap Co (Uninc)	600	700	800	900	1,000	1,200
Arap Co (Urban)	28,800	35,900	37,400	39,900	48,100	79,300
Arvada	58,300	80,800	89,600	94,800	100,500	117,400
Aurora	78,200	121,700	140,800	157,000	175,200	228,700
Boulder City	78,400	92,200	98,800	106,700	115,500	130,100
Boulder Co (E Uninc)	8,700	13,300	14,700	17,300	19,600	24,700
Bow Mar	1,000	1,100	1,300	1,300	1,300	1,300
Brighton	8,300	12,900	16,000	18,000	20,000	25,000
Broomfield	7,700	16,400	24,200	29,700	35,600	44,500
Cherry Hills Village	4,600	5,400	7,500	8,300	9,100	10,700
Columbine Valley	500	600	600	600	600	600
Commerce City	17,400	18,600	19,500	19,500	19,800	20,000
Denver	520,200	532,300	543,900	566,100	588,600	646,700
Edgewater	4,900	5,500	5,500	5,600	5,600	5,900
Englewood	33,700	35,900	38,900	40,900	42,900	45,900
Erie**	-	100	100	300	500	800
Federal Heights	1,500	7,600	9,100	9,900	10,800	12,900

**Allocation for part in Boulder County only; total service area forecasts are:

1975 - 1,300	1990 - 2,000
1980 - 1,800	2000 - 2,200
1985 - 1,900	

TABLE C-16 (Concluded)

Service Area	Base 1970	Current 1975	1980	Short Term 1985	1990	Long Term 2000
Valley (Cont'd)						
Glendale	800	3,700	8,700	8,700	8,700	8,700
Golden	9,800	14,500	16,200	18,600	21,000	26,000
Greenwood Village	2,600	3,500	4,200	5,200	6,500	10,000
Jefferson (A-P)***	8,200	9,500	10,600	11,600	12,700	15,200
Jefferson (SE Urban)	9,100	21,200	40,900	68,200	96,600	137,900
Jefferson (Uninc)	100	200	4,000	6,000	8,000	12,000
Lafayette	4,100	5,800	8,500	10,200	11,900	14,000
Lakewood	95,100	123,000	148,900	163,700	176,700	213,600
Lakeside	****	****	****	****	****	****
Littleton	27,700	33,500	36,300	38,000	40,100	47,300
Longmont	23,200	34,200	42,100	46,300	53,200	67,400
Louisville	2,800	3,700	6,200	10,000	13,600	13,600
Morrison*	400	500	500	600	700	800
Mountain View	700	800	800	800	800	800
Northglenn	27,900	31,500	34,300	36,700	37,800	38,600
Sheridan	4,800	6,000	6,600	8,100	9,500	13,200
Superior	200	300	300	400	400	500
Thornton	15,500	27,600	35,500	39,500	44,800	65,500
Westminster	21,600	31,600	36,500	40,700	45,400	58,900
Wheat Ridge	29,800	34,300	38,000	40,000	42,000	47,000
5-County Region	1,229,800	1,473,800	1,650,200	1,802,500	1,968,800	2,350,000

***A-P - Applewood-Pleasantview.

****Less than 50.

the Cycle 3 figure (705,200). Analysis of local and regional development plans indicated that both Cycle 3 and Cycle 4 underallocated growth in Boulder County. The SAP allocation of 287,900 to Boulder is well above the earlier allocations (245,000 and 257,000). In Adams and Arapahoe Counties, the SAP allocation is closer to that for Cycle 4. In Jefferson County the reverse is true: the SAP is closer to Cycle 3. This latter point is helpful from the point of view of air quality analysis, since most available traffic data is based on Cycle 3. The prevailing southwest to northeast wind during the morning rush-hour period also emphasizes the importance of emissions in the southeast part of Jefferson County (southwest of Denver).

The above discussion details both the development and detailed results of the population allocation efforts most currently in use in the Denver regional planning process. If the SAP represents the institutionally endorsed plan while available emissions data is based on Cycle 3 or Cycle 4, careful attention must be paid to both the staging and level of differences. While the above paragraph indicates that in Jefferson County the SAP, much closer to Cycle 3, may be compatible with transportation planning, this may not be true in Denver County. The SAP in that county is closer to Cycle 4. This would suggest Cycle 3 might have higher emissions in the downtown area. Without a more detailed breakdown of the differences in population allocation, however, and some idea of their work-leisure driving patterns, any statement of definitive conclusions is premature. It is, nevertheless, helpful that all three allocation plans sum to the same year 2000 regional population.

The staging of population growth is also an important factor in planning analyses. Much of the difference in Denver County between Cycle 3 and Cycle 4/SAP, for instance, comes in the decade 1980-1990. Growth in Arapahoe County, on the other hand, comes primarily in the decade 1990-2000. Growth in southeast Jefferson County is high in the beginning and middle years of the study period, tapering off toward the end.

c. Land Use Planning

Land use planning is intertwined with population planning, pacing the level, distribution and staging of growth. Its importance as an issue in planning, however, well exceeds the size of the discussion devoted to it in this report. This is due primarily to the apparent uniformity of adherence throughout regional planning agencies to the land-use plan adopted by the JRPP/DRCOG in January of 1974. Although in the intervening time since then a number of issues have emerged which may cause the DRCOG to reexamine its adopted plan, such action will probably not occur during the time-frame of this Overview EIS. It is thus important to understand the policy issues underlying the approved plan.

As described in Reference 10, seven policy statements were enumerated at the time of the adoption of the land use plan by the DRCOG, acting on behalf of the JRPP. First, a Year 2000 population below 2,350,000 should be encouraged. Second, the Central Business District (CBD) of Denver should be considered the "major high density core of business, cultural, governmental, commercial and residential activity," with major high density corridors running east, west and south from the CBD. Third, the development of several major activity centers should be encouraged in the Metropolitan Area. Fourth, new, low density residential growth should be encouraged only in locations contiguous to existing urban areas. Fifth, new industrial development should be encouraged only to the extent suitable locations can be found where environmental hazard potential can be effectively controlled or minimized. Sixth, major unique urban areas should be encouraged to remain distinct, i.e., "not to ultimately be allowed to expand and run together into a nondescript, low density urban sprawl." Seventh, major areas of "ecological, environmental, agricultural, historic and archeological significance" should remain in a natural open or low-density, non-urban condition.

The DRCOG stated that the purpose of the land use plan was not to replace local plans but to provide a framework of guidelines within which local decisions could be made. It expressed, however, concern that the surge in in-migration and residential construction encountered in the early 1970's had resulted in the conversion to single and multiple family residential use large parcels of formerly agricultural or vacant land. The DRCOG noted that this had generated concern over the undesirable effects of urban sprawl.

A major planning concept advanced by the JRPP adopted plan was that of activity centers. These were designed to be aggregations of urban activity great enough to be primary generators of large internal activity. The DRCOG considered them to be "a key tool by which the Regional Plan can be achieved." A map of the JRPP Land Use Plan, presented earlier in the report, is repeated for convenience in Figure C-21. The activity centers are denoted on it by circles.

It was conceived that the activity centers would create distinct nodes of higher level activity and services throughout the region. By orderly location of that activity, it was hoped some development pressure could be relieved on the urban fringes and also provide impetus for redevelopment of currently depressed areas. The provision of activity centers would also allow a large portion of the individuals living within the areas to live and work there. Each activity center was considered to extend through an area of about one mile in radius. A list of the activity centers recommeded by staff to the DRCOG is presented in Table C-17, from Reference 10.

The plan also recommends two high intensity land use corridors to be served by a fixed guideway public transportation system. As noted in a previous section, such a system was recommended by the RTD, but funding was denied by UMTA. The first corridor was proposed to lie east and west of the CBD along Colfax Avenue from Kipling Avenue on the west to I-225 on the east. The other corridor was to extend southward from the CBD to Englewood along a route paralleling Broadway. They ranged in width from one-quarter to one-half mile.

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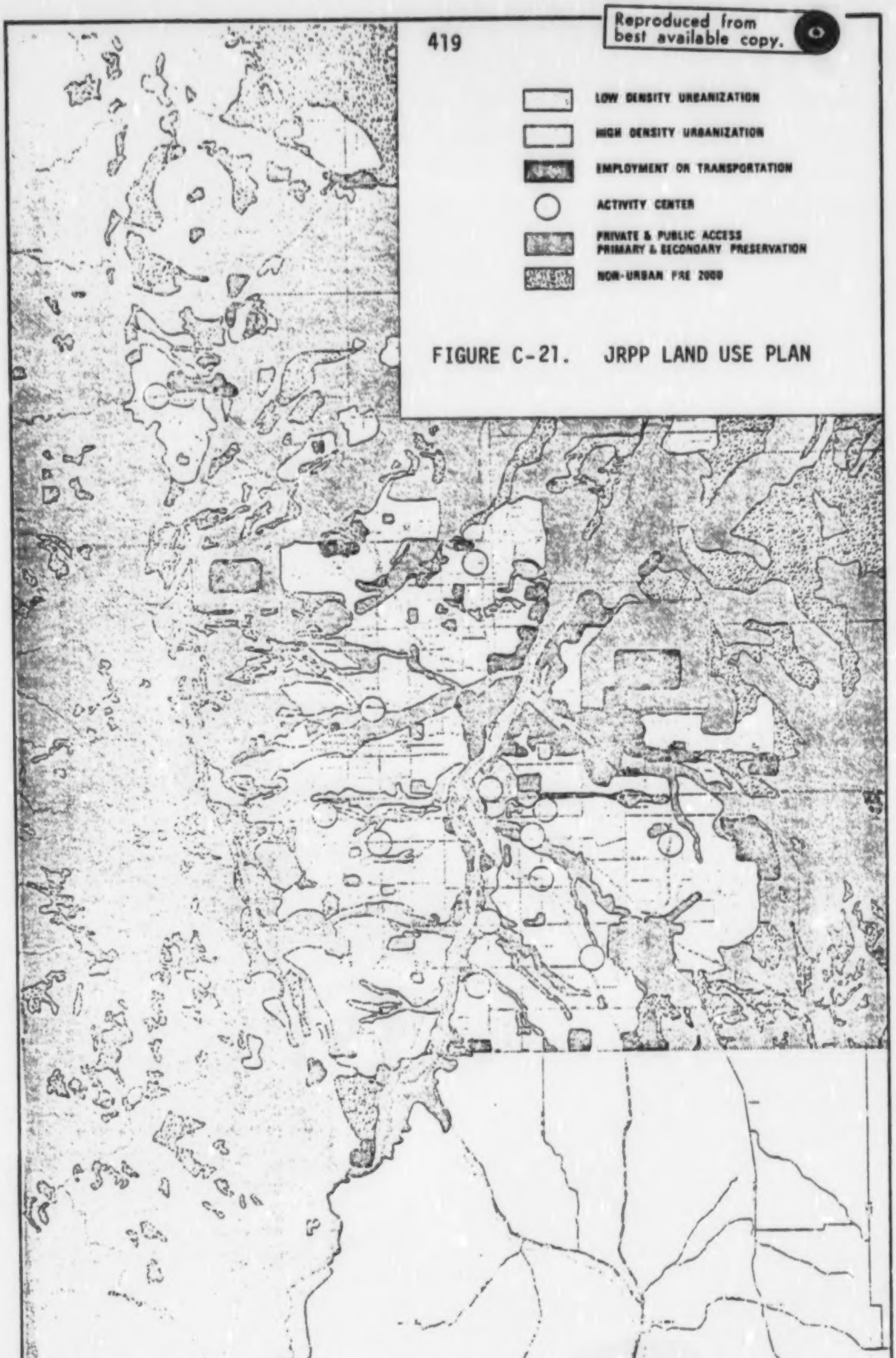
LOW DENSITY URBANIZATION
HIGH DENSITY URBANIZATION
EMPLOYMENT OR TRANSPORTATION
ACTIVITY CENTER
PRIVATE & PUBLIC ACCESS PRIMARY & SECONDARY PRESERVATION
NON-URBAN PRE 2000

FIGURE C-21. JRPP LAND USE PLAN

TABLE C-17. ACTIVITY CENTERS FOR JRPP LAND USE PLAN

Center	General Location
Boulder	University of Colorado/Crossroads Shopping Area/ CBD
Northglenn	Northglenn Shopping Area/Western Electric Front Range Denver Area
Arvada	Old CBD/Tri-Center Area
Federal Center	Federal Center/Community College/Westland Areas
Villa	Villa Italia Vicinity
Alameda	Alameda/I-225 Area
Denver CBD	CBD/Auraria/Skyline
Medical Center	CU Medical Center/Colorado-Colfax Area
Cherry Creek	General Cherry Creek Shopping and Residential Area
South Colorado	Colorado Blvd./I-25 Area
Englewood	Englewood CBD/Cinderella City Shopping Center
Technological Center	General Area of Denver Technological Center/ Greenwood Plaza
Littleton	Littleton CBD Area

The plan does not explicitly address future employment, leaving that subject to local governments. It does attempt to identify those areas most desirable from a regional perspective. Public parks and recreational areas are shown on the map in Figure C-21, forming a component of the Open Space Plan.

From an air quality perspective, two features of the JRPP Lane Use Plan have particular significance, the first explicit, the second implicit. The first concern is the identification of those land areas in which fixed-source emissions can be expected to occur. In the map in Figure C-21, these regions are designated as "High Density Urbanization" and "Employment or Transportation." The second feature of the plan of concern is the activity center and corridor element. Areas of such intense activity have a sizeable indirect impact on the frequency and distribution of vehicle travel. The resulting highway loading parameters are strong determinants of air quality. A more explicit description of the twelve activity centers and the three travel corridors in the JRPP Land Use Plan is provided by Figure C-22 and Table C-18, both from Reference 19.

It should be kept in mind, however, that the activity center concept has been relaxed in recent planning efforts. Transportation planners noted, for instance, that using the concept in attempts to model the traffic network leads to distortions in the traffic assignment process by which trips are loaded onto roadway links. Also, since the UMTA decision not to fund a fixed guideway transit system, the RTD has had to reorient its plan to incorporate an all-bus Year 2000 transit plan. This is certain to be a factor in a revisiting of the JRPP Land Use Plan expected to occur in the next year.

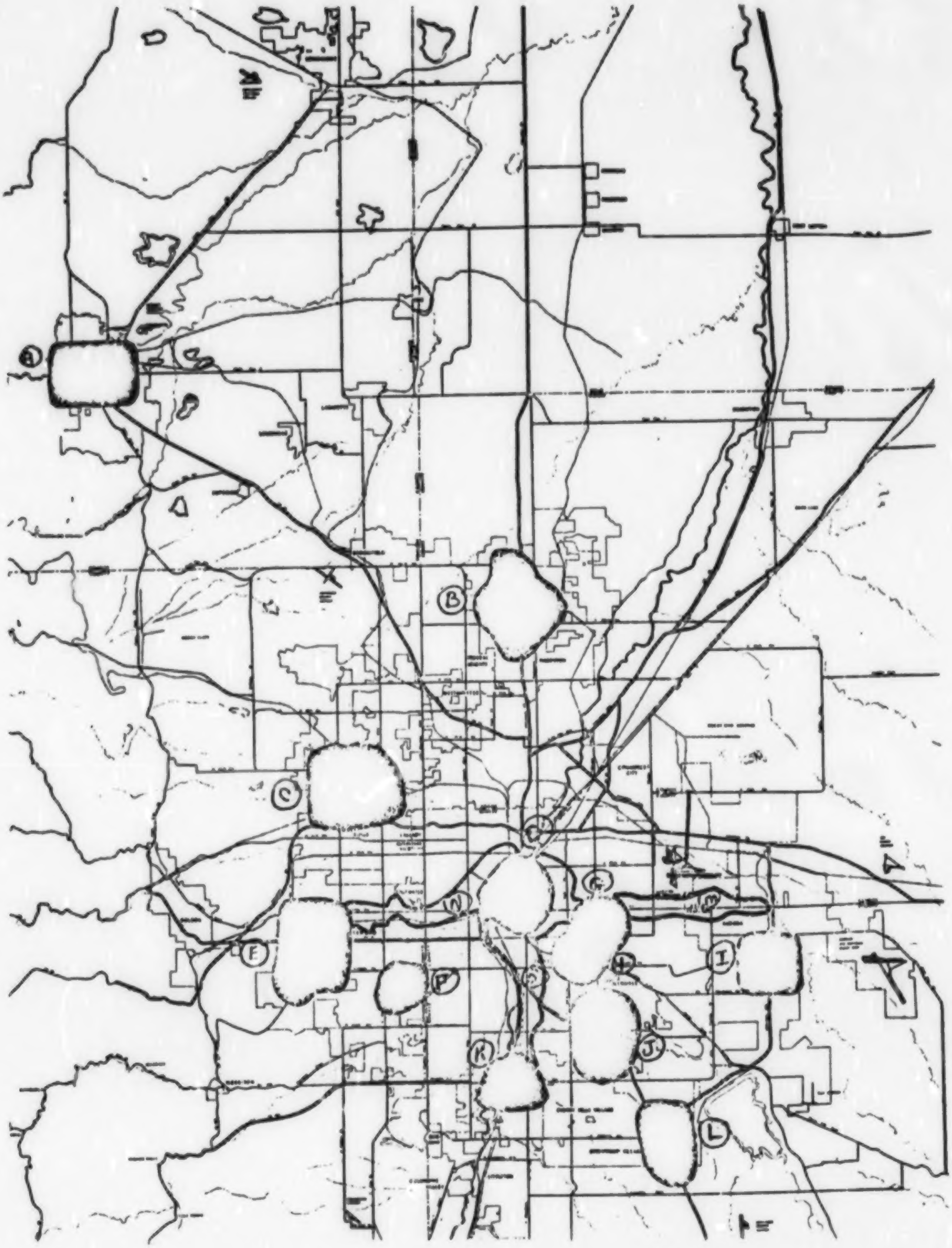
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FIGURE C-22. ACTIVITY CENTER AND CORRIDOR LOCATIONS (JRPP LAND USE PLAN)

TABLE C-18. ACTIVITY CENTERS AND TRAVEL CORRIDORS (JRPP LAND USE PLAN)

Activity Centers and Corridors	Primary Functions	Current Population	2000	Current Employment	2000 Employment	2000 Persons DU/G.A.	2000 DU/G.A.
A. Boulder	Shopping/employment/educational/housing	32,000	39,000	20,000	26,000	15.3	5.1
B. Northglenn	Shopping/employment/housing	23,000	54,000	5,000	21,000	16.8	5.6
C. Arvada	Shopping/employment/housing	28,000	47,000	5,000	16,000	21.9	7.3
D. Denver CBD-Auraria	Employment/shopping/educational/cultural/institutional/housing	27,000	40,000	78,000	85,000	22.5	7.5
E. Federal Center-Westland	Employment/shopping/housing/institutional	14,000	27,000	13,000	20,000	9.3	3.1
F. Villa Italia	Shopping/employment/housing	15,000	26,000	4,000	16,000	20.1	6.7
G. C.U. Medical Center	Institutional/employment/housing	25,000	42,000	14,000	25,000	30.9	10.3
H. Cherry Creek	Shopping/employment/housing	12,000	24,000	8,000	14,000	23.7	7.9
I. New Aurora	Shopping/employment/institutional/housing	10,000	16,000	500	5,000	13.5	4.5
J. Writers Manor-University Hills	Employment/shopping/housing	35,000	49,000	11,000	32,000	12.0	4.0
K. Englewood	Shopping/employment/institutional/housing	16,000	27,000	10,000	19,000	22.2	7.4
L. Tech Center	Employment/shopping/housing	2,000	33,000	2,000	36,000	26.1	8.7
M. East Colfax Corridor	Employment/shopping/housing	47,000	81,000	15,000	39,000	43.2	14.4
N. W. Colfax Corridor	Employment/shopping/housing	29,000	64,000	12,000	30,000	27.6	9.2
O. S. Broadway Corridor	Employment/shopping/housing	45,000	64,000	18,000	23,000	35.1	11.7

d. Transportation Planning

It is the results of the transportation planning process that have the most direct influence on regional air quality. Agreed upon regional population level, distribution and staging lead to design of a highway network, supplemented by a rapid transit system, able to accommodate anticipated travel levels and distribution, both temporal and spatial. Both the vehicle-miles-traveled (VMT) and the average speed along each highway link determine the amounts of carbon monoxide (CO) and hydrocarbons (HC) emitted into the surrounding air. The problems resulting from highway design are particularly acute because of the extensive ownership and use of private automobiles in the Metropolitan Denver region.

In this section the transportation planning process will be explored in some detail. The discussion will be presented in two parts. The first will deal with the physical transportation network alternatives. Two such plans exist: the DRCOG-adopted JRPP Highway Plan used by the DRCOG, the CDH, and the APCD; and the Existing plus Committed (E+C) used by the RTD as an alternative in planning their rapid transit network. The second part of the transportation planning discussion will consider the problems inherent in transportation modeling and the uncertainties introduced by the various modeling iterations, principally within the DRCOG staff.

1) Transportation Networks

The JRPP Highway Plan, repeated here as Figure C-23 from Reference 10, was originally adopted in December 1973 by the DRCOG acting as the Policy Body for the JRPP. The other member agencies, CDH and RTD, approved it in January 1974. It has been incorporated along with Cycle 3 population allocation into the transportation planning efforts of the DRCOG and the CDH. It has also been used by the APCD, although in conjunction with Cycle 4 population allocation.

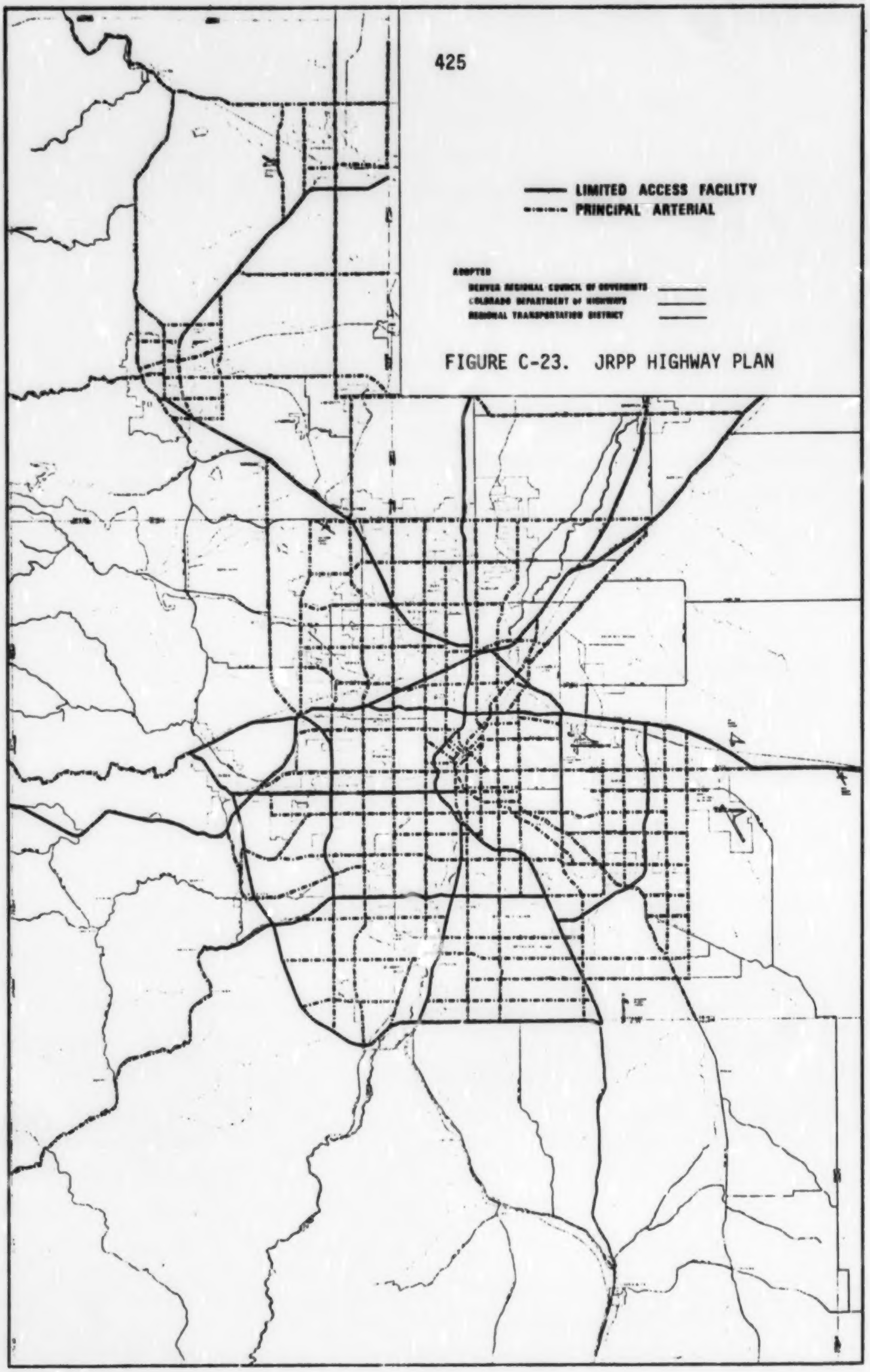
LIMITED ACCESS FACILITY
PRINCIPAL ARTERIAL
ADOPTED
DENVER REGIONAL COUNCIL OF GOVERNMENTS
COLORADO DEPARTMENT OF HIGHWAYS
REGIONAL TRANSPORTATION DISTRICT

FIGURE C-23. JRPP HIGHWAY PLAN

The highway plan was conceived as a systems plan, identifying general corridors rather than specifying detailed construction plans. It was designed as a package to be presented for approval at the same time as the Regional Land Use and Public Transportation Plans. The three were designed to complement each other. The Highway Plan, with its grid of principal arterials, spaced one to two miles apart, and its grid of limited access arterials, spaced four to five miles apart, was to serve the lower density developments, while the public transportation system was to serve the higher density areas. The Highway Plan provided for the addition of 80 miles to the limited access facilities. Major elements of that addition are detailed in Table C-19, as abstracted from Reference 10. Some of the routes on the principal arterial system were identified as needing extensive widening or construction.

In developing the above-mentioned complementary land use, highway, and public transit plans, the staff for the DRCOG, acting on behalf of the JRPP, considered six alternatives for the distribution of urban activities within the Denver region. The six were: (1) Continue Existing Trends, (2) Reinforce Central Denver, (3) Reinforce Metropolitan Centers, (4) Reinforce Regional Centers, (5) Stimulate Development of New Towns, and (6) Dispersal. According to Reference 19, it was decided not to use computer oriented or extensive simulation techniques in the evaluation and analysis of the six alternatives. Such efforts were judged inappropriate at the level of concept specification.

For each of the alternatives, a transportation system was conceived. Each was then evaluated to determine its impacts on the region. These impacts were measured against parameters formulated from an analysis of local community goals and objectives and regional goals adopted by the DRCOG. The resulting generalized conclusions about the success or failure of the six alternatives in meeting local and regional objectives produced a synthesis of the six into one land development and transportation concept. An iterative process refined this concept into specific regional land use and transportation plans. This process included discussions with local officals and groups.

TABLE C-19. NEW LIMITED ACCESS FACILITIES (JRPP HIGHWAY PLAN)*

Interstate 470: This facility will serve the anticipated growth in Southern Jefferson County, Arapahoe and Douglas Counties.

Interstate 225: This facility will be completed from Parker Road to I-25.

Interstate 25: This is, and will continue to be, the most heavily traveled freeway in the region.

Interstate 80S: This facility will connect Interstate 25 with Interstate 70 and will follow the Clear Creek flood plain.

Hampden Avenue: This facility will service the east-west travel in the southern portion of the Denver Metropolitan Area. A detailed location study will be required between Santa Fe Drive and Interstate 25 before the facility can finally be located.

Santa Fe Drive: This facility, long discussed as the "Columbine Freeway," is needed to serve the travel needs of the developing south and south-western portions of the Metropolitan Area. The facilities implementation will have to be coordinated with that of the construction of the rapid transit line which uses the same corridor.

Kipling: This facility is being planned as an arterial by the City of Lakewood. The City of Wheat Ridge strongly opposes its construction. The expansion of this arterial to a limited access facility will have to carefully consider the highway's economic and environmental benefits and costs.

Quebec: This facility, from I-70 to Parker Road, will require extensive citizen participation and environmental design before it will meet the travel and community needs of the area affected. This element is placed on the regional plan pending more detailed analysis that must be done by the Joint Regional Planning Program and the Colorado Division of Highways.

Longmont Diagonal: This facility will connect Longmont with I-25 and the City of Boulder.

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* From Reference 10.

The transportation concept arising out of the above process took specific form through analysis of regional travel demand corridors. Computerized traffic assignment techniques and transportation models were used to evaluate the resulting highway and public transportation alternatives. Nine computer tests of these alternatives were conducted and used in the plan development work. The tests were referred to as 1971, 2000 Base Case, 2000 Concept, A-1, A-2, A-3, A-4, A-5, and 2000 Comparative Case. The 1971 test was used to calibrate the model against observed data. The Base and Comparative Cases were tested for comparisons with the plan test. The 2000 Concept represented the initial plan but the "new town" concept was subsequently eliminated. The tests denoted A-1, A-2, A-3, and A-5 were then used to select the preliminary plans. The A-4 test with an updated "new towns" component was used as a comparison against the preliminary plans. The assumptions embedded in each of these tests are presented in Table C-20 from Reference 19.

As mentioned earlier in this section, a basic feature of the land use plan resulting from the DRCOG/JRPP analysis was the concept of activity centers. These were viewed as localized centers of high-intensity urbanized activity. They were included with the high density travel corridors and other intense centers of development to catalog a list of major traffic generators. A map of these major traffic generators is shown in Figure C-24, with a list showing projected trip-ends presented in Table C-21. Both are from Reference 19.

TABLE C-20. ASSUMPTIONS OF POLICIES AND CONSTRAINTS ASSOCIATED WITH EACH CASE

	Base Case	Comparative	A-1, A-2, A-3, A-5 Concept-New Towns	Concept A-4 Concept-No New Towns	*Alternative
Urban Form	Sprawl	Sprawl	Activity centers, activity corridors, new towns	Activity Centers, activity corridors	As close to activity centers & corridors as possible
Environment					
Development Policy	Limited control	Limited Control	Strong control "radical" new legislation	Strong control	Strong control
Activity Parameters					
1. Population	2,097,100	2,097,100	1,899,900	2,097,100	2,097,100
2. Employment	1,104,400	1,104,400	848,800	1,049,000	1,049,000
Highway System	Existing priorities Level of Service ≥ C	LAF, principals Level of Service ≥ C	LAF, principals Level of Service < C	LAF, principals Level of Service < C	LAF, principals Level of Service < C
Transit System	Extended Denver Metro Transit	Extended Denver Metro Transit	PRT	PRT	All bus-but new technologies & concepts and/or limited PRT
Financial Restraints					
1: Transit	None	None	1.0 Billion	1.0 Billion	1.0 Billion
2. Highway	[redacted] Yes	None	None	None	None
Political-Public	None	None	No LAF Central No LAF on Wadsworth, few new LAF's	No LAF Central No LAF on Wadsworth, few new LAF's	No LAF Central Denver NO LAF on Wadsworth few new LAF's

LAF - Limited Access Facility
PRT - Personal Rapid Transit

*Proposed

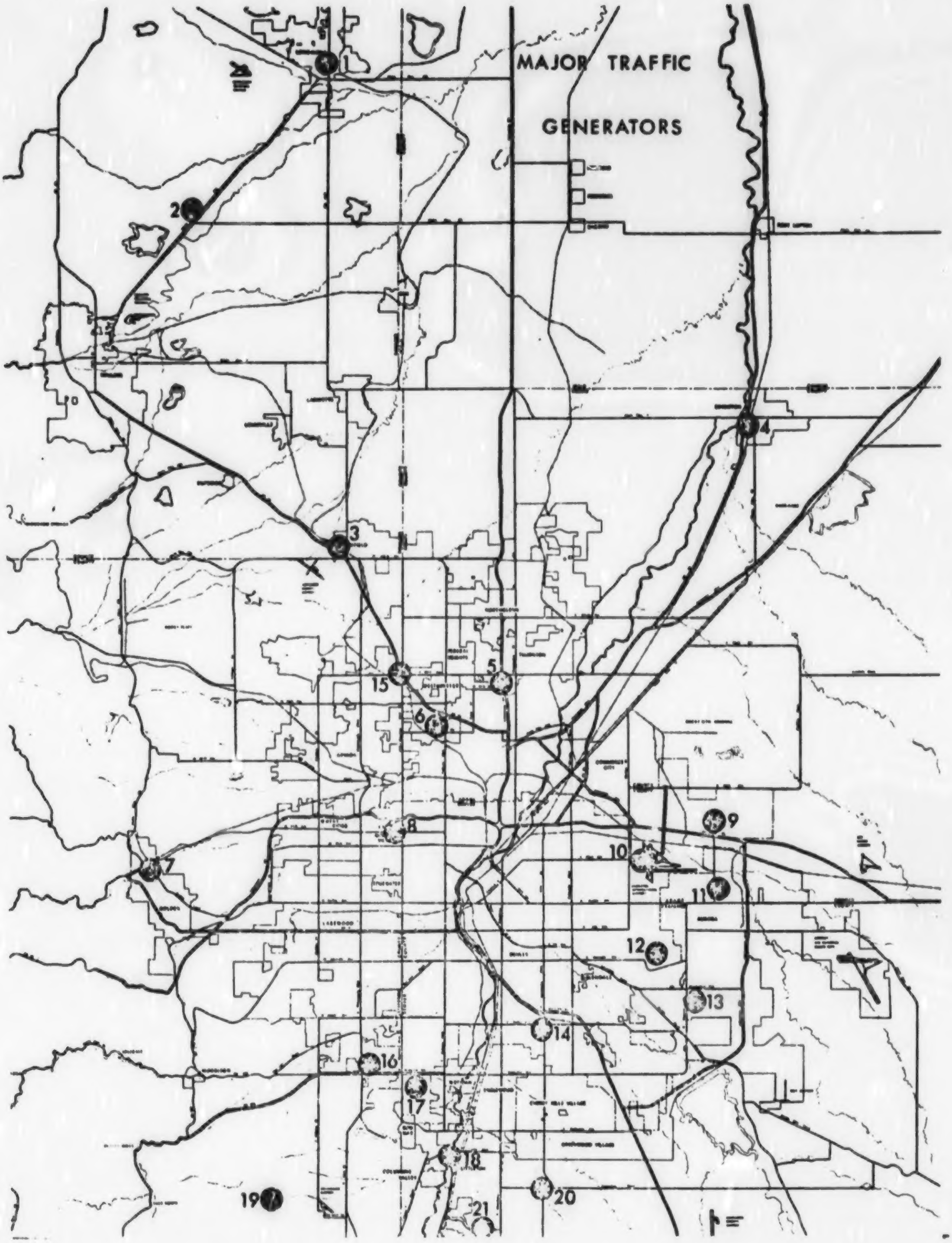
MAJOR TRAFFIC GENERATORS
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FIGURE C-24. MAJOR TRAFFIC GENERATORS (JRPP HIGHWAY PLAN ANALYSIS)

TABLE C-21. LOCATIONS OF MAJOR TRAFFIC GENERATORS (JRPP HIGHWAY PLAN ANALYSIS)

		1970 Trip Ends	2000 Trip Ends
1.	Longmont CBD	17,700	26,800
2.	IBM at Niwot	14,200	35,000
3.	Broomfield CBD	25,600	49,400
4.	Brighton CBD	8,900	20,000
5.	North Valley S. C./Valley View Hospital	13,800	52,500
6.	Westminster Plaza	16,200	35,800
7.	Golden CBD/Coors	35,900	39,700
8.	Lakeside S. C.	18,600	22,800
9.	Montbello	40,800	126,200
10.	Stapleton International Airport	30,800	71,400
11.	Fitzsimmons Hospital	30,000	21,300
12.	Lowry Air Force Base	58,400	55,000
13.	Buckingham Square S. C.	0	31,600
14.	Denver University	35,000	35,000
15.	Sheridan & 88th S. C.	14,000	47,100
16.	Bear Valley S.C.	8,700	22,800
17.	Fort Logan Hospital	8,300	20,000
18.	Littleton CBD	33,100	89,500
19.	Johns-Manville	0	111,000
20.	Southglenn S.C.	7,100	18,700
21.	Gates Industrial Park	900	20,000
22.	Martin Marietta	24,800	42,800

In the JRPP analyses the Denver region was divided into districts for transportation planning purposes. A map of the individual districts as conceived in 1972 is presented in Figure C-25 from Reference 19. Aggregation into super-districts was also performed. Boundaries of those super-districts are shown in Figure C-26 with population and employment information provided in Table C-22, also from Reference 19. Year 2000 population and employment density on a regional basis are shown in Figures C-27 and C-28, from Reference 21 as prepared for the RTD.

It appears that the plan ultimately adopted by the DRCOG on behalf of the JRPP corresponds fairly closely with the alternative referred to as A-5 and shown in Figure C-29. It seems to have been used in an analysis of rapid transit networks performed by the DRCOG staff in 1972-73. Preliminary estimates indicated a construction cost for the highway plan of about $960,000,000. New construction areas are indicated in Figure C-30.

A second highway plan has since emerged from within the Regional Transportation District. Much of the rationale for the new plan came from air quality analyses carried out for RTD by Systems Management Contractor. During the latter phase of that work in early 1975, the E+C network was introduced for comparison with the JRPP plan, presumably in the event that the JRPP highway construction program proved unrealistically optimistic from a funding point of view. This was in response to the urging of UMTA representatives reviewing RTD alternatives. The E+C network so defined consisted of existing roadways and those new construction projects for which funding had already been committed.

Several principal features of the JRPP plan have already run into difficulties. Opposition arose some time ago to the I-470 circumferential highway. At best federal funding seems delayed. A detailed assessment report on I-470 was not filed until September of 1976. Also, UMTA recently has denied federal funding for the fixed guideway rapid transit system proposed by the RTD. The impact this will have on highway planning has not yet been assessed, though it is possible that higher levels of automobile traffic might result.

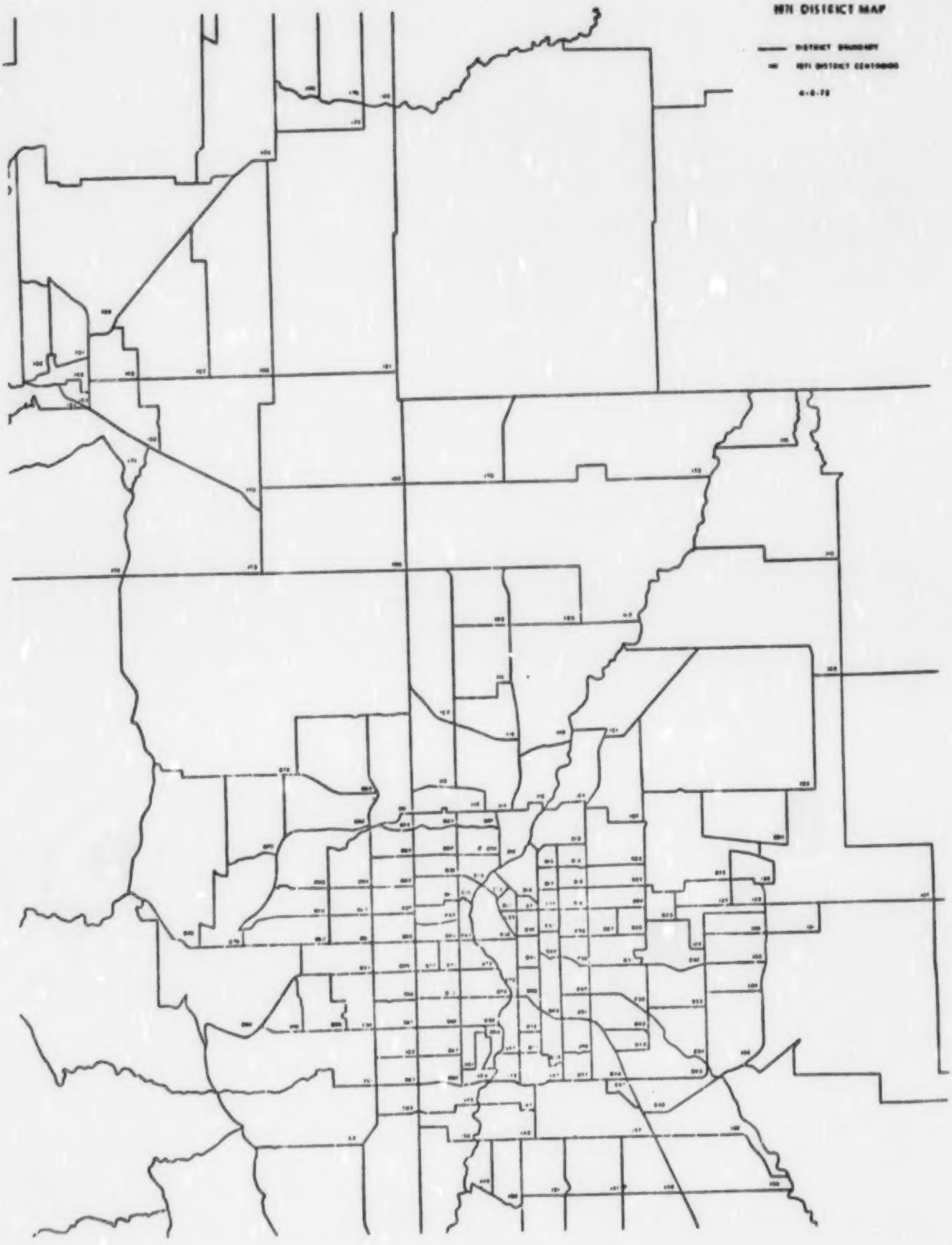
1971 DISTRICT MAP
DISTRICT BOUNDARY
1971 DISTRICT CENTROIDS

FIGURE C-25. TRANSPORTATION ANALYSIS DISTRICTS
(JRPP HIGHWAY PLAN)

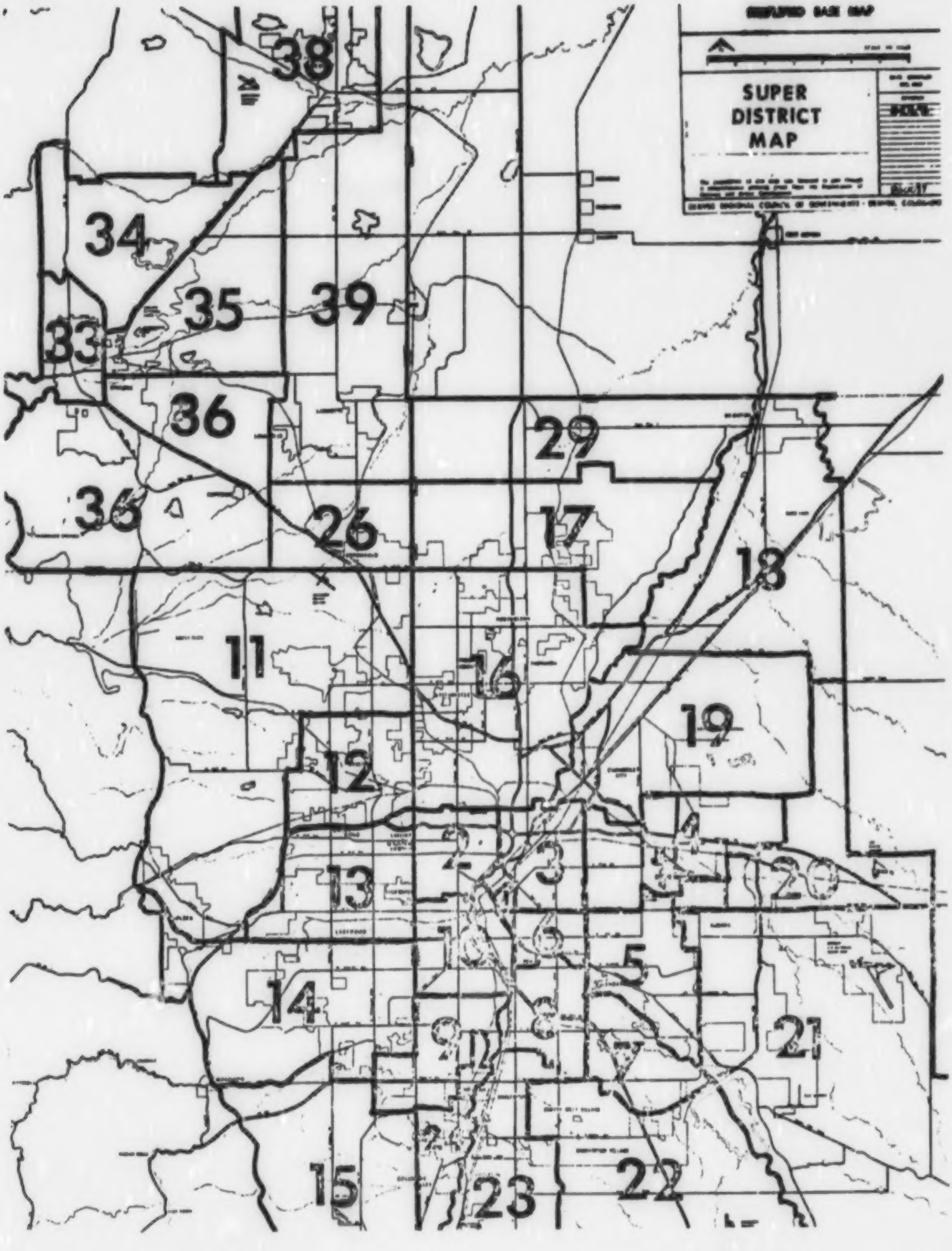
SUPER
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FIGURE C-26. TRANSPORTATION ANALYSIS SUPER-DISTRICTS
(JRPP HIGHWAY PLAN)

TABLE C-22. POPULATION AND EMPLOYMENT BY SUPERDISTRICT

	1970		Compar.		2000 Plan	
Super Dist.#	Pop x 1000	Emp. x1000	Pop.	Emp.	Pop. x 1000	Emp. x 1000
1	3.1	47.9	3.6	46.2	7.0	50.2
2	64.7	16.8	62.4	43.7	67.2	46.3
3	61.4	58.9	58.9	85.1	78.6	75.5
4	40.8	25.1	57.0	48.7	70.7	46.0
5	51.8	32.6	74.4	72.1	90.9	32.6
6	62.6	30.3	64.9	40.0	98.8	40.0
7	42.9	14.0	60.1	37.8	80.4	39.5
8	63.2	19.6	63.1	47.7	85.1	48.0
9	52.9	8.8	54.5	40.3	68.2	32.0
10	74.5	52.9	72.2	61.4	97.8	55.5
11	26.2	17.0	94.0	43.2	77.0	35.0
12	48.5	8.5	77.6	23.2	78.0	21.0
13	74.1	23.5	94.3	39.4	122.7	39.5
14	55.5	16.5	126.7	36.7	106.2	44.0
15	8.3	7.4	104.0	26.8	62.5	24.0
16	112.5	31.8	211.8	68.6	210.5	60.5
17	1.2	.7	21.0	9.7	14.2	7.5
18	11.1	3.1	25.0	7.8	15.0	5.0
19	28.3	10.4	30.1	21.9	23.0	21.0
20	28.9	8.9	64.3	24.4	54.4	19.5
21	49.0	12.0	149.4	48.7	135.4	40.5
22	20.4	5.7	132.4	62.4	103.5	74.4
23	67.5	26.8	87.6	52.8	113.0	50.5
24	19.4	4.7	32.9	18.0	26.0	15.5
25	.3	.1	1.7	.3	1.7	.5
26	8.4	2.9	19.0	13.8	18.5	12.0
29	.7	.3	14.0	4.7	2.8	1.7
33	36.6	19.6	57.6	26.9	47.4	29.5
34	1.1	4.0	5.2	5.7	8.0	5.6
35	6.5	5.2	24.2	11.9	17.0	12.3
36	17.7	2.2	52.0	11.1	27.5	8.1
37	18.5	2.8	38.0	5.4	26.1	8.3
38	25.6	8.5	45.0	14.3	42.7	20.5
39	9.4	.7	35.0	9.2	16.3	4.6
40	.4	--	1.0	.5	3.0	.2
Total DBL	1,194.0	530.2	2,114.9	1,110.4	2,097.1	1,026.8

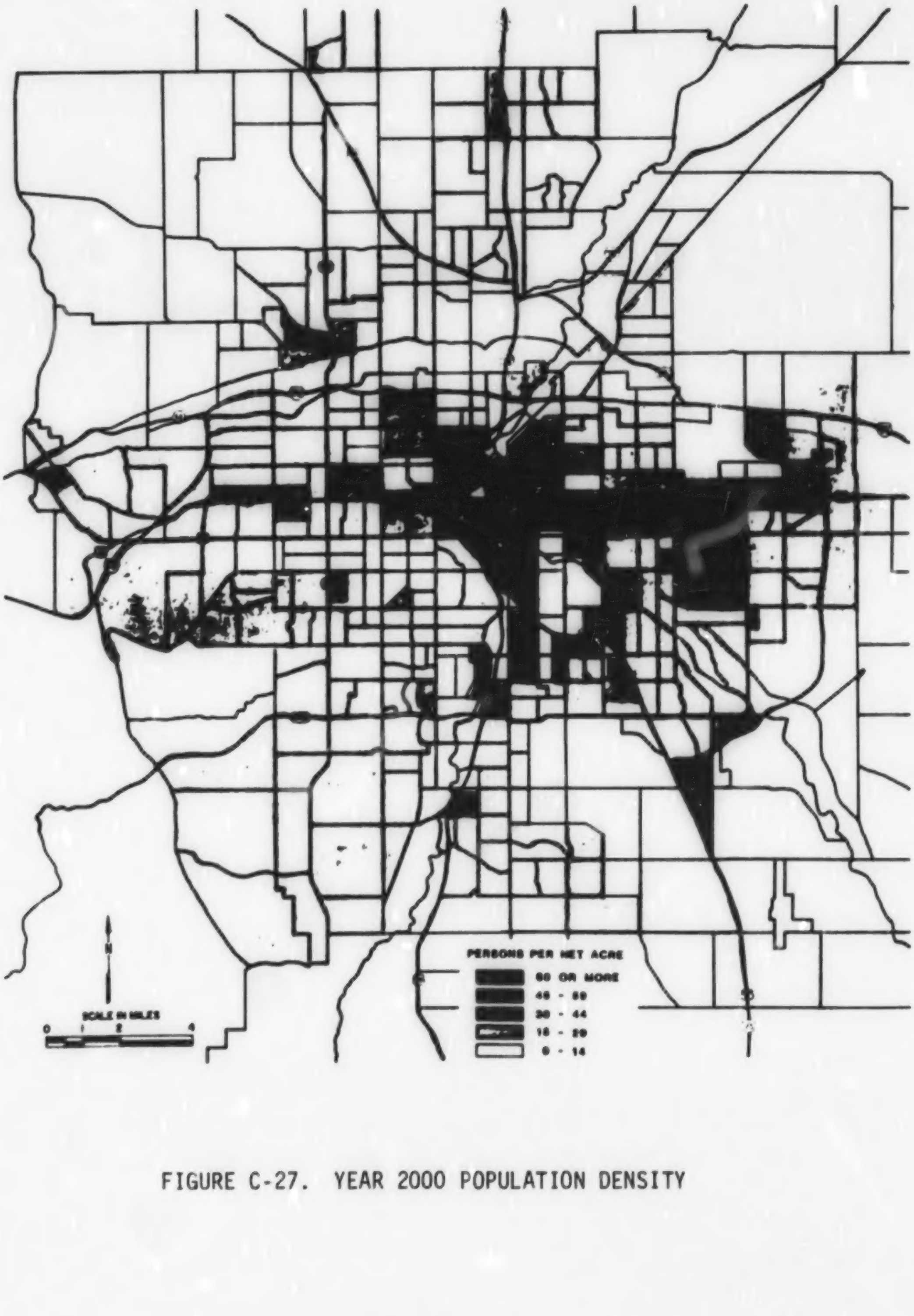
N
SCALE IN MILES
0
1
2
4
PERSONS PER NET ACRE
60 OR MORE
45 - 59
30 - 44
15 - 29
0 - 14

FIGURE C-27. YEAR 2000 POPULATION DENSITY

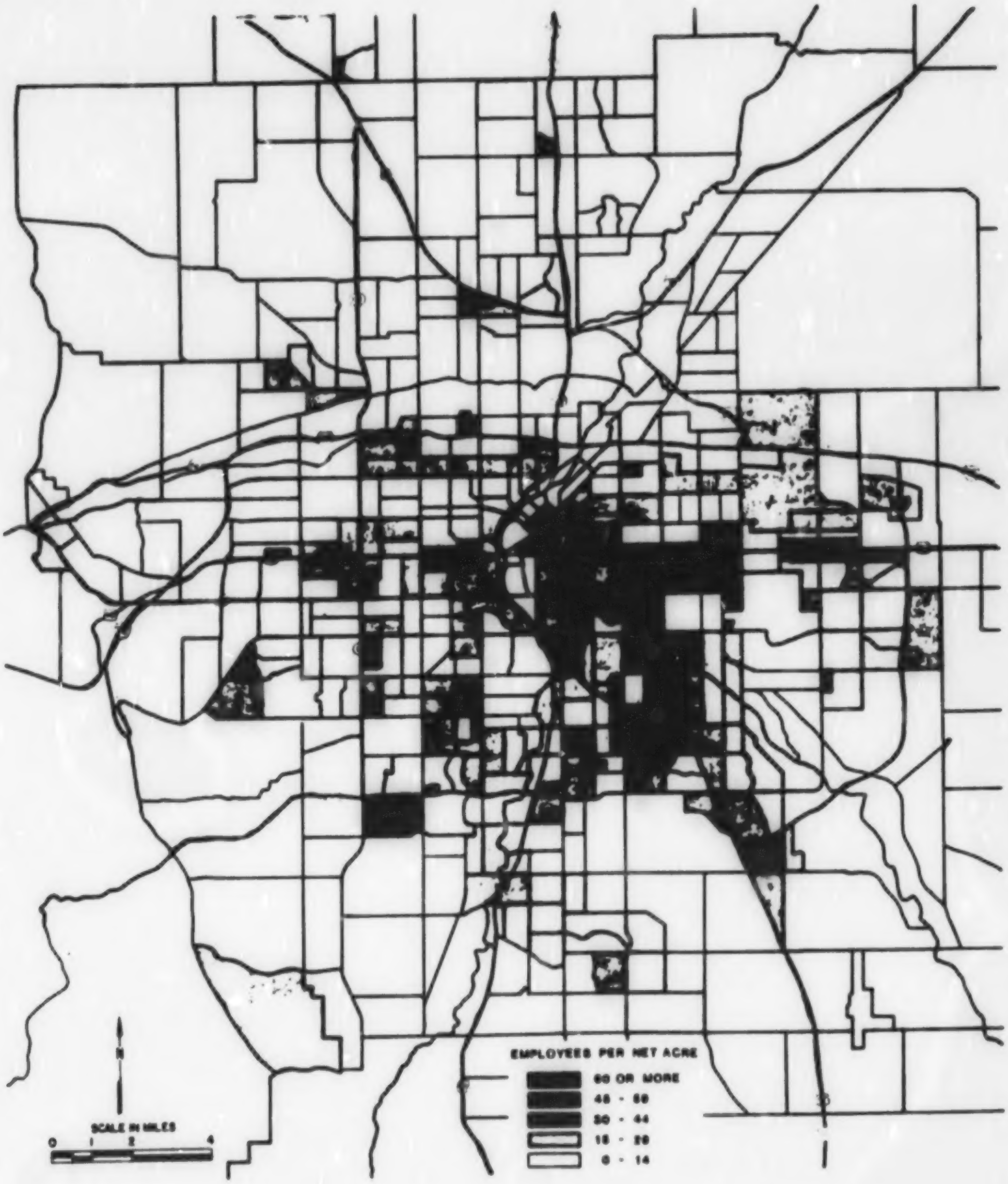
N
SCALE IN MILES
0
1
2
4
EMPLOYEES PER NET ACRE
60 OR MORE
45 - 59
30 - 44
15 - 29
0 - 14

FIGURE C-28. YEAR 2000 EMPLOYMENT DENSITY

Reproduced from best available copy.

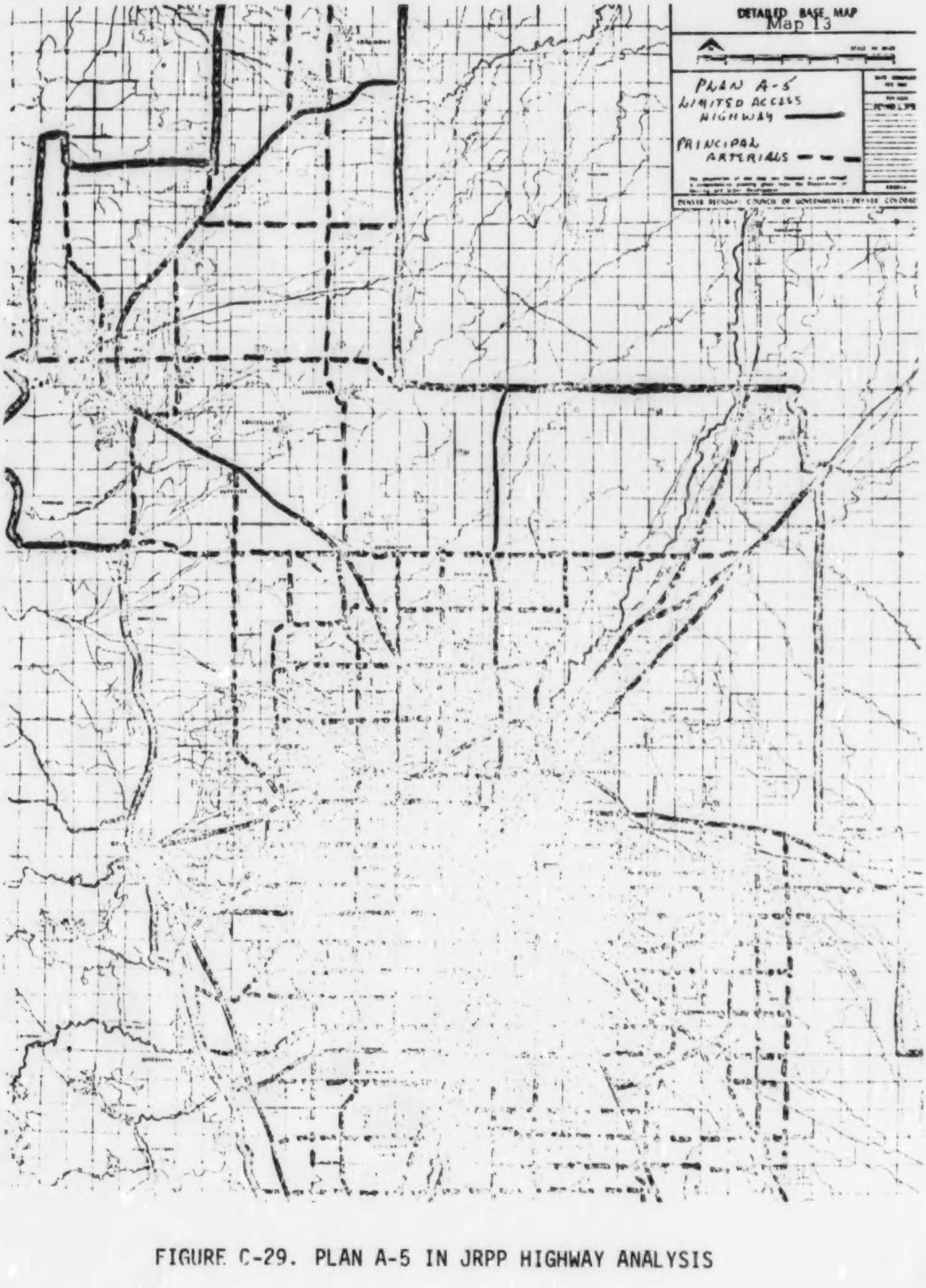
DETAILED BASE MAP
Map 13
PLAN A-5
LIMITED ACCESS HIGHWAY
PRINCIPAL ARTERIALS
DENVER REGIONAL COUNCIL OF GOVERNMENTS · DENVER, COLORADO

FIGURE C-29. PLAN A-5 IN JRPP HIGHWAY ANALYSIS

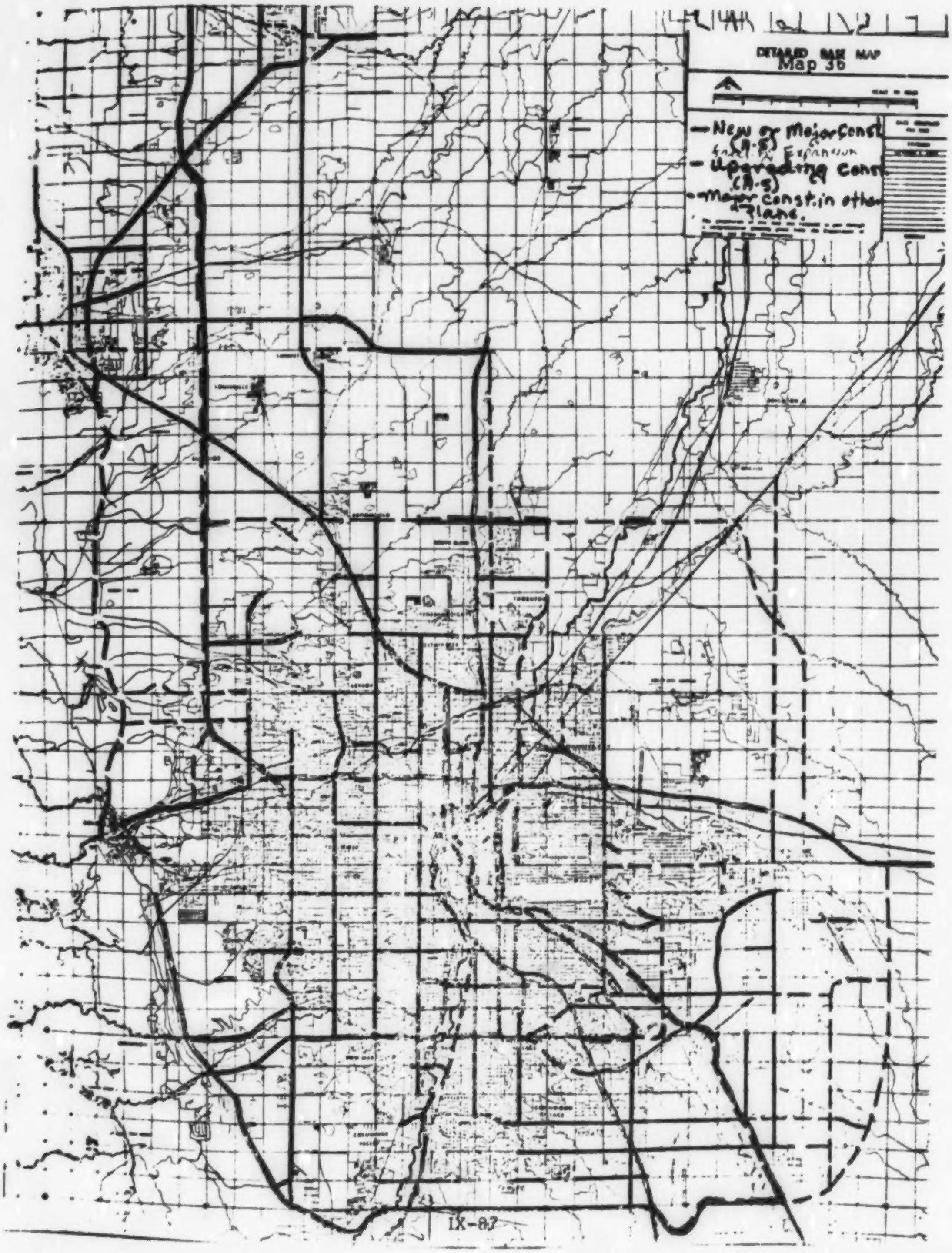
DETAILED BASE MAP
Map 36
— New or Major Const. (A-5)
Sand Cr Expansion
— Upgrading Const. (A-5)
— Major Const. in other Plans.
IX-87

FIGURE C-30. NEW CONSTRUCTION FOR PLAN A-5 IN JRPP HIGHWAY ANALYSIS

2) Transportation Modeling

Even once population (level, allocation and staging), land use, and highway network configuration have been agreed upon, the transportation planning process is not complete. The vehicle trips--their number and distribution, both spatial and temporal--taken by that population must be forecast and the resulting vehicle-miles-traveled (VMT) assigned to links on the roadway network. The important parameters from an air quality standpoint are both the VMT and the average roadway speed on each link of the highway system for each hour of the day. Using these quantities, vehicle emissions--CO, NO_x and HC--can be determined.

A brief word about the modeling process itself is helpful prior to reviewing the status of specific model results. In an effort to quantify the gradients of "travel desire" that lead to trip generation, the geographical region of interest is devided into a gridwork of traffic zones. There are 654 such zones in the Metropolitan Denver region, for example. Each of these has been paired with every other to establish a relative ranking of attractiveness. The result is a matrix of interzonal attractions used as weighting factors in assigning total forecast VMT in individual areas and highway links.

Having modeled the relative attractiveness of individual areas, it is necessary also to determine the number and type of trips generated between zones. This is done by first stratifying trips by type. Then the number of trips of each type are determined by relating each to the various socio-economic characteristics of the people taking them. This is frequently done through regression analysis relating trip type and level to such variables as land use, household type and size, population and family size, and employment. Typical trip types are the following: home based (work, shopping, other); non-home based; truck; external-internal (to and from outside the modeled region); and external-external (through traffic). Also, reliance is often place on Origin and Destination (O&D) surveys, the last one of which was completed in Denver in 1971.

The distribution of the trips generated by the above methods is determined by examining the propensity of people to travel. Since travel time is perceived as a cost, most people prefer to travel as short a time as possible in performing a given trip function. Their disincentive with increasing distance or time can be expressed in probabalistic terms by a trip length distribution curve incorporating the concept of average trip length. Also, in determining the pattern of trip-taking, modal split must be considered, i.e., the relative proportions of trips taken by private vehicles and public transit. Since costs are perceived somewhat differently by the users of both modes, different trip length distributions are modeled.

The final component of the modeling process is the trip assignment process. As a preliminary to this, it is necessary to determine minimum time or distance paths between each of the traffic zones. Travelers desiring trips between any two traffic zones are then assumed to prefer these optimal paths. Some modeling algorithms simply assign all such trips to the same path up to the capacity of the roadway links along that path. Excess trips are then off-loaded to next-best paths. More sophisticated models attempt to account for congestion effects by assuming that at some point prior to traffic reaching full capacity drivers begin to voluntarily avoid that path, off-loading onto secondary routes. When that point will occur and how far drivers will be willing to detour in distance or time again depends on their trip length distribution function.

After validation and calibration against known roadway loading data (trip counts), a model comprised of the previously described four components is ready for use, the trip generation, trip distribution, modal split and trip assignment segments all functioning properly. Among the planning agencies in the Denver region, three evolutionary versions of such models have been used, referred to as the first, second, and third generation transportation models.

Early modeling efforts within the JRPP were conducted within legal time constraints imposed upon the RTD. As a result the initial version of the model was completed before results of the regional 1971 Origin and Destination survey were processed. Two distinct generations of modeling thus were used, the first (1st Generation) based on the results of a 1959 O&D survey and the second (2nd Generation) incorporating 1971 data as it became available. The 2nd Generation Model also incoporated more sophisticated algorithms.

It is the differences between the 2nd and 3rd Generation Models that have direct significance to the current planning process, however. Transportation modeling results upon which most planning has been based within the DRCOG, the CDH, and the RTD were generated by the 2nd Generation Model. Emissions data available from those agencies for air quality analysis is thus 2nd Generation vintage. To the extent the 3rd Generation Model produces different results (link VMT and speed), the air quality analysis may also differ, although the kinetics of air pollution chemistry can exhibit pronounced non-linear behavior. Also, a summary of the differences between the 2nd and 3rd Generation models is particulary important because recent DRCOG transportation studies have begun to incorporate the 3rd Generation Model. Significant difference seems to exist between total daily VMT projections in the year 2000: 38,000,000 VMT per day with the 2nd Generation Model and just under 30,000,000 VMT per day with the 3rd Generation Model. This is a gross difference of over twenty percent.

According to a recent letter from David Pampu, the Assistant Director for Planning for the DRCOG, to William Geise, Jr., Chief of the Environmental Evaluation Branch of the EPA, Region VIII, the differences between the two transportation models can be summarized as follows. The theoretical bases of the two models were developed independently. The 2nd Generation Model was based on the Pratt Marginal Utility Model. This 3rd Generation Model, also known as the Unified Travel Patterns Model, was based on the n-Dimensional Logit Model.

Network building procedures are similar in both models, each using UMTA discrete network link coding methods. The chief difference in this area lies in the means of accounting for the disfavor in which the public holds mass transit. The 2nd Generation Model explicitly accounts for this through disutility weighting factors. The arbitrariness introduced through the choice of these factors was removed by eliminating them in the 3rd Generation Model.

Trip generation is similar in both models. The only difference lies in the elimination in the 3rd Generation Model of a separate trip category for airline passengers. Revised estimates of airline traffic have greatly reduced the regional significance of this trip category.

Even though both generations use a gravity model, the algorithm used for trip distribution represents the most significant difference between the 2nd and 3rd generations. The 2nd Generation Model distributes trips by trip purpose (but not by income) independently over the highway and transit system. It then uses a balancing technique after modal split to combine the trip tables for both. The 3rd Generation Model, on the other hand, utilizes a single composite network representing the three available modes: auto driver, auto group and transit passenger. A compound impedance is formed by summing the inverse of the inverses of the individual mode impedances, i.e., summing link impedances in parallel. Trips are then distributed over this theoretical network by trip purpose and by income.

Differences exist in modal split methods as well. The 2nd Generation Model uses manual curve fitting technique to relate transit ridership to a logarithmic form equation in which transit travel time and costs are subtracted from auto totals. The 3rd Generation Model utilizes a partially disaggregate modal choice model (used to account for travel time cost). The probability of using a mode is then assumed equal to the individual impedances, raised to the base "e," divided by the sum of the impedances, each raised to the base "e."

Traffic assignment is also performed differently, with important variances arising. Although both models utilize a capacity restraint function, the 2nd Generation Model simply reloads the entire trip table three times and then averages the results. As a consequence, the process tends to overload the freeway system. The speed table input was chosen to represent calibrated speed for 1971. Because the model could only lower speeds and not raise them, successive program iteration resulted in speeds that were considered by the DRCOG to be "very low." The 3rd Generation Model, however, uses an initial Level of Service speed table and an incremental loading process. With this method ten percent of the trip table is loaded onto the network, speeds are recalculated, and then the next ten percent of the trip table is loaded. Successive application of this process results in both less overloading of the freeway network and a more accurate representation of speed.

In air quality terms the most significant differences are the daily link VMT and speed histories. As mentioned earlier the forecast of total VMT in the year 2000 is 38,000,000 for the 2nd Generation Model and about 30,000,000 for the 3rd Generation Model. It seems that the differences in the models distill down to shorter trips and higher overall speeds (for the same highway and transit network). This would suggest that use of results from the 2nd Generation Model might be somewhat more conservative from an air quality perspective, since greater mileage and lower speeds both can have detrimental effects on pollutant emissions.

It also seems clear that future DRCOG transportation modeling efforts will employ the 3rd Generation Model. A Year 1975 model validation run is nearly complete. A run incorporating the Year 2000 JRPP Plans is planned next. The first iteration has been performed, with completion expected in early December. Intermediate year runs can be expected in the Spring of 1977.

4. SUMMARY AND RECOMMENDATIONS

a. Summary

This task report has been intended as an overview of the planning process in the Metropolitan Denver region, specifically considering those planning issues and agencies having crucial bearing on air quality. Because the analyses to be performed by SAI will be so heavily driven by the assumptions underlying the input data supplied to it and because several permutations of that data exist within the agencies providing it, a precise, detailed examination of the relevant planning issues is an essential preliminary to the study process.

The results of this task report will be drawn upon heavily in structuring SAI's analysis efforts. Specifically, a base case regional development scenario must be identified along with a complete catalog of the important uncertainties associated with it. A carefully constructed sensitivity analysis must then be conducted to examine the air quality effects of as broad a range of these uncertainties as possible. This report, through its examination in some depth of the critical elements of regional planning, will assure the broadest perspective in SAI's efforts.

Brevity in this section is as important as attention to detail was in the last. Adhering to that principle, it is sufficient to outline by use of a table the status of planning within each agency having input to the air quality analysis. In Table C-23 such a summary is provided. Also, in Figure C-31, a schematic is presented illustrating those planning alternatives that have a bearing on air quality analysis.

b. Recommendations

Since the pollutant emissions files available for input to the SAI model are provided by the Colorado Division of Highways, and because

TABLE C-23. SUMMARY OF TRANSPORTATION PLANNING ASSUMPTIONS

Agency	Study Vintage	Population*	Land Use	Transportation Plan	Transportation Model
Denver Regional Council of Governments (DRCOG)	1973 JRPP Plan analysis	Cycle 3	JRPP Plan (Cycle 3)	JRPP Plan	2nd Generation
	Current	Subarea Allocation Plan	JRPP Plan	JRPP Plan	3rd Generation
Colorado Division of Highways (CDH)	Current and Last Several Years	Cycle 3	JRPP Plan (Cycle 3)	JRPP Plan	2nd Generation
Regional Transportation District (RTD)	Early Transit Study (1974)	Cycle 3	JRPP Plan (Cycle 3)	JRPP Plan	2nd Generation
	Later Transit Study (1975) and Current	Cycle 3	JRPP Plan (Cycle 3)	Existing Plus Committed (E+C)	System Management Contractor (SMC) n-Dimensional Logit
Air Pollution Control Division, Health Department (APCD)	Denver AQMA Study (1975)	Cycle 3	JRPP Plan (Cycle 3)	JRPP Plan	2nd Generation
	Current	Cycle 4	JRPP Plan (Cycle 4)	JRPP Plan	2nd Generation

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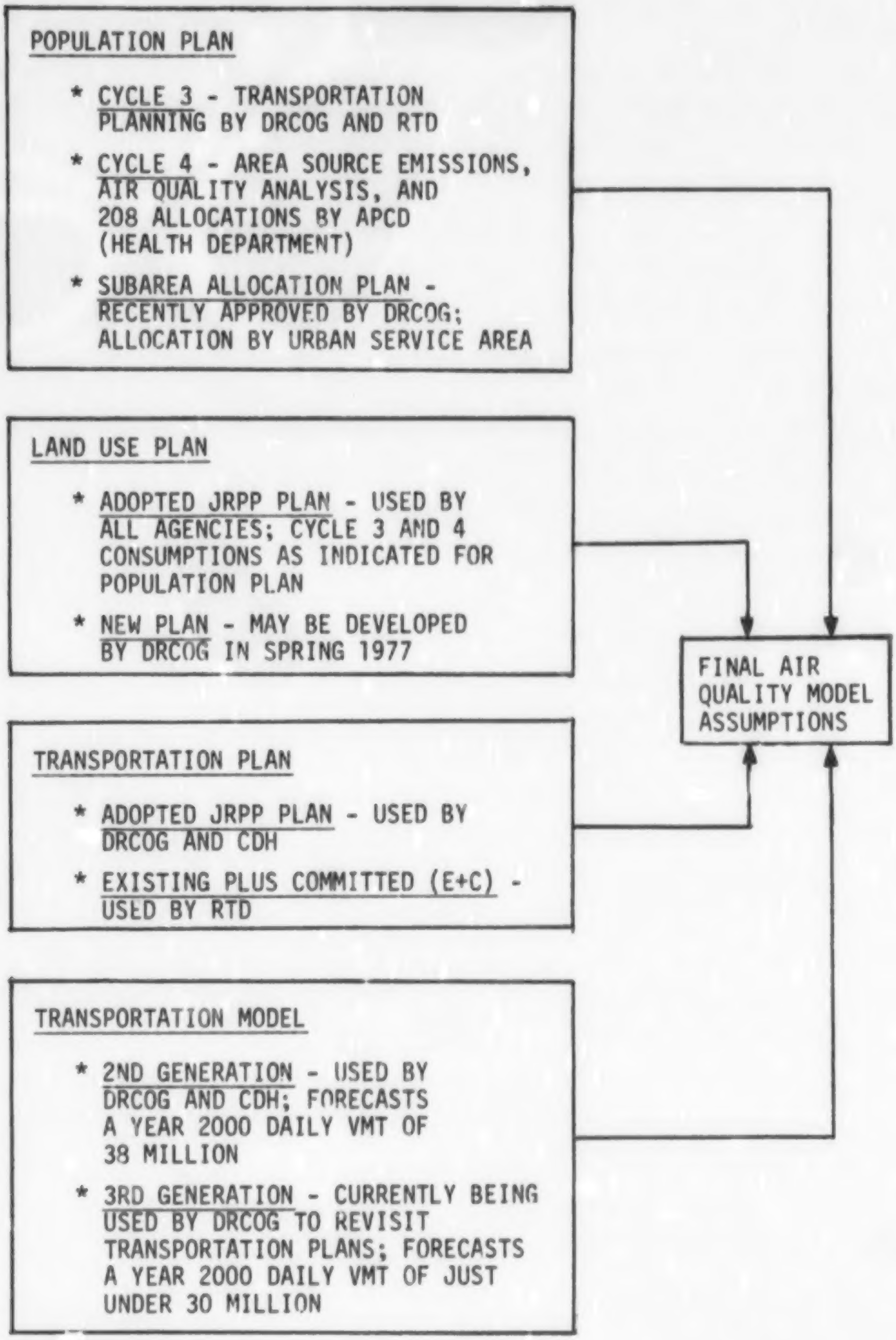
* All population allocation plans shown here total 2,350,000 in the year 2000.



POPULATION PLAN

- CYCLE 3 - TRANSPORTATION PLANNING BY DRCOG AND RTD
- CYCLE 4 - AREA SOURCE EMISSIONS, AIR QUALITY ANALYSIS, AND 208 ALLOCATIONS BY APCD (HEALTH DEPARTMENT)
- SUBAREA ALLOCATION PLAN - RECENTLY APPROVED BY DRCOG; ALLOCATION BY URBAN SERVICE AREA

LAND USE PLAN

- ADOPTED JRPP PLAN - USED BY ALL AGENCIES; CYCLE 3 AND 4 CONSUMPTIONS AS INDICATED FOR POPULATION PLAN
- NEW PLAN - MAY BE DEVELOPED BY DRCOG IN SPRING 1977

TRANSPORTATION PLAN

- ADOPTED JRPP PLAN - USED BY DRCOG AND CDH
- EXISTING PLUS COMMITTED (E+C) - USED BY RTD

TRANSPORTATION MODEL

- 2ND GENERATION - USED BY DRCOG AND CDH; FORECASTS A YEAR 2000 DAILY VMT OF 38 MILLION
- 3RD GENERATION - CURRENTLY BEING USED BY DRCOG TO REVISIT TRANSPORTATION PLANS; FORECASTS A YEAR 2000 DAILY VMT OF JUST UNDER 30 MILLION

FIGURE C-31. PLANNING ALTERNATIVES HAVING A BEARING ON AIR QUALITY neither time nor funds exist for alternative transportation modeling runs, in practical terms it is their assumptions that define a base case. As shown in Table C-23, data from the CDH has embedded in it Cycle 3 population allocation, the adopted JRPP land use and transportation plans, and the use of the 2nd generation transportation model. It is important that the sensitivity analysis conducted about this base case consider variations wide-ranging enough to encompass the important alternatives to this set of assumptions.

It appears that the differences in population allocation are most pronounced in the high growth areas, e.g., southeast Jefferson County, Lakewood, Aurora, and the urban portion of Arapahoe County. In reviewing the magnitude of those differences a perspective should be maintained about the allocation alternatives. Cycle 4, as an extension of Cycle 3, can be assumed to have corrected some of the faults of that version. Its use would thus seem more current. However, only the Subarea Allocation Plan (SAP) has been formally approved by the DRCOG, and it was recommended by their staff for use in the Denver Regional Clean Water Program for the final Water Quality Management Plan. This latter point suggests that participants in the water quality elements of the Overview EIS may find necessary the use of the Subarea Allocation Plan figures.

Fortunately, from an air quality point of view, Cycle 3 and the SAP are fairly close in Jefferson County. Although the information reviewed thus far presents this conclusion only on an aggregate county-wide basis, if the comparison between the two holds uniformly throughout the county, southeast Jefferson County, Lakewood, Arvada, and parts of Westminster can be assumed comparable between Cycle 3 and the SAP. This is particularly helpful in southeast Jefferson County, since the prevailing southwest-to-northeast flow of wind during the morning rush hour can emphasize the effect of emissions in that region.

Cycle 3 and the SAP do not agree well in Denver County, where the SAP allocation more closely approximates Cycle 4. The chief difference seems to lie in the assumption of low growth in the county in Cycle 4 and the SAP. A sensitivity analysis about a base case using Cycle 3 might therefore consider varying population related emissions in Denver County. If, however, the allocation difference can be idealized as distributed uniformly throughout the county, localized effects could be considerably diminished due to the county's relatively large surface area. With such a simplifying assumption, incorporation of such differences in the sensitivity analysis might not be necessary.

Allocation differences in Adams and Arapahoe Counties might be considered in the sensitivity analysis. However, staging in the high growth area of Arapahoe County indicates such growth will not occur until 1990-2000, well after attainment of Federal air quality standards will be required. Also, growth in Adams County seems to be most likely in Aurora, particularly in the southeast part of the city. Due to the prevailing winds, emissions from this area would be expected to have different effects than would emissions closer to the Denver CBD.

It should be noted that each of the three allocations sum to 2,350,000 in the year 2000, since this figure is a cornerstone in DRCOG/JRPP planning. To the extent this figure may be too high, due to declining birth rate or inmigration levels, emissions may also be too high, though not necessarily by any linear relationship. Long-term historical trends suggest that both these population effects seem possible, although it may still be premature to so conclude. Some accounting, however, for uncertainties in the population level could be made in the sensitivity analysis by adjusting population by some uniform factor on a regional basis.

A serious obstacle lies in the way of a direct examination of the effects of these allocation differences, just as it does for the effects of differences in land use and transportation plans. The most pronounced effects of growth on air quality lie in automobile usage patterns and VMT levels. Additional population in an area, however, may produce its increased auto emissions in some other area. This is particularly true during rush-hour commutes. Varying emissions in the growth areas then may not consider all the detrimental effects on air quality that growth might produce. The only analytically consistent way to model such effects is to use a full transportation model to reload the altered population level onto the roadway system. Since the Overview EIS has neither time nor money to perform large scale variations using a complete transportation model, a simpler surrogate for such models must be sought.

The highway network assumed for the planning process can provide clues for inferring the highway usage patterns of incremental population amounts. Growth in outlying suburbs, for instance, might be expected to travel inward during the morning rush hour towards either the Denver CBD or one of the other employment centers. Since relatively long distances are involved, it might further be anticipated that such travel would occur on freeways or principal arterials. The link-node representation of the highway network could be used to isolate those links over which travel might occur. Emissions along these routes could be adjusted in a sensitivity analysis, thus avoiding a major reloading of the transportation model.

Clearly differences in the highway network can have pronounced effects on pollutant emissions, as the traffic redistributes itself on the roadway system. Implied in the base case identified earlier is the use of the JRPP Highway Plan. Objections to this plan were raised by UMTA during the RTD planning process. They suggested that the E+C network might represent a more realistic roadway system. Whether or not this is true, the extensive transportation modeling analysis required to make such modifications seems prohibitive in the time frame of the Overview EIS. Air quality results then will have to be judged with the highway network as an implied caveat.

Other things being equal, it would seem that loading a given VMT onto a smaller roadway system, such as the E+C network, could increase congestion considerably and elevate pollutant levels much more than proportionally. The base case would seem from this standpoint an optimistic one. Air quality results might well be more favorable, although the interdependence of travel patterns, VMT and congestion could alter considerably the level and distribution of growth.

Another significant area of uncertainty is that due to the transportation modeling process. Projections of total daily VMT in the year 2000 differ by as much as twenty percent between the 2nd and 3rd generation models, a considerable amount. Once again the extensive modeling expense, time and effort needed to consider these differences in a sensitivity sense seem beyond the resources of the Overview EIS. Preliminary results of the 3rd Generation Model, however, suggest for the JRPP highway network that trips are shorter, a conclusion supported by the lower Year 2000 daily VMT totals. This could lead to an easing of roadway congestion and higher link speeds. The error involved in using the 2nd Generation Model over the 3rd Generation Model, however, is in the opposite direction from that resulting from use of the JRPP highway network over the E+C network. The two errors seem countervailing, although not at all necessarily compensating.

This final discussion has been intended to raise and examine a number of the issues that must be considered in structuring the air quality analysis. Though much remains to be resolved, it is only the level of detail in this task report that permits the subtleties involved in the planning process to be recognized. It should also be obvious that many of the issues raised in the discussion of the sensitivity analysis are also applicable to the analysis of mitigation measures. The important uncertainties must be accounted for in both. The issues, however, remain the same. It is hoped that this report has shed a useful illumination upon them.

ANNEX C-1

A SIMPLIFIED POPULATION FORECASTING METHOD

a. Introduction

Growth--how much and where it will be distributed--is at the heart of the planning process, serving as a key determinant of the level and staging of demand for public services. Because of this importance, considerable effort is usually expended in its determination. Detailed models are frequently used to forecast population level and cross-section, stratifying individuals by age group and applying in a probabalistic sense the appropriate age-group fertility and death rates as well as migration levels. Such models divide population into two components: net natural increase (the net of births over deaths), which is proportional to the current population; and migration, which is an annual level, usually historical and assumed independent of current population. This type of population level forecasting is often referred to as a "direct" method, and an example of it is the "cohort-survival" technique used as the basis of DRCOG efforts in the Metropolitan Denver region.

Because of the complex set of assumptions embedded in these models, their projections are often difficult to assess. For this reason it is helpful to distill the full set of assumptions down into two more conceptually convenient parameters: net natural increase and migration. All of of the more complex assumptions about fertility and death rates by age-groups can be collapsed into a single composite net natural increase rate which can be applied directly to the aggregate current population. Migration can similarly be reduced to a single aggregate level.

The above procedure allows the development of a simplified population projection method, useful for forecasting total population levels. Though not as accurate as a fully stratified "cohort-survival" model, results of the simplified procedure developed in this discussion compare favorably with the aggregate population levels forecast by the DRCOG using the more complex model. It also provides a convenient means to evaluate analytically sensitivities of population forecast to the net natural increase rate or the migration level.

In the following pages, the simplified method will first be derived, sensitivities will be determined, and finally a brief review of the DRCOG final forecast population will be presented.

b. Derivation of the Simplified Method

The simplified method relies for its final closed-form solution on the decomposition of the population growth problem into two parts. The first, the net natural increase rate, is assumed to be proportional to the current population. The second, the migration level, is assumed to be a fixed annual figure independent of the current population. In relational terms the differential equation incorporating these assumptions can be written as

$$\dot{P} = rP + m \quad , \qquad (1)$$

where $\dot{P}$ is the instantaneous rate of change of the total population, P is the current population, r is the net natural increase rate, and m is the migration level.

This equation can be directly integrated to solve for the time-varying form followed by total population. To do so, it must be recognized that the solution to Eq. (1) has two components, one a solution to its homogeneous form and the other a particular solution. The homogeneous form of Eq. (1) is

$$\dot{P}_h = rP_h \qquad (2)$$

which has as its solution

$$P_h = Ae^{rt} \quad , \tag{3}$$

where A is constant whose value is determined by the problem's boundary conditions. By inspection, the particular solution to Eq. (1) has the form

$$P_p = -\frac{m}{r} \quad . \tag{4}$$

Applying the superposition principle the homogeneous and particular solution to Eq. (1) can be summed to give the full solution, i.e.,

$$P = Ae^{rt} - \frac{m}{r} \quad . \tag{5}$$

The initial boundary condition, i.e., $P(t_o) = P_o$, can be applied to solve for the unknown constant, A . The value of A thus determined is

$$A = \left(P_o + \frac{m}{r}\right)e^{-rt_o} \quad , \tag{6}$$

where P_o is the population in the initial year of the simulation period.

Substituting Eq. (6) into Eq. (5) yields the final form of the solution, i.e.,

$$P = \left(P_o + \frac{m}{r}\right)e^{r(t-t_o)} - \frac{m}{r} \tag{7}$$

It is this equation that expresses the growth of total population over time.

Results of this equation can be verified by comparing them with several alternatives considered by the DRCOG. In their "Appraisal of the DRCOG Policy Population Forecast" (August 1975), the staff of the DRCOG detailed the eight alternative population growth cases that they considered in their studies. Case IV, for instance, assumed a net natural increase rate between 1970 and 2000 of 8.5/1000 persons (1972 rate) and a migration leval of 42,000 persons annually (the 1970-73 average level). The resultant 1980 and 2000 populations were 1.8 and 3.0 million, respectively. The simplified form in Eq. (7), using the same assumptions, reproduced these values to the same level of significance.

As another example, Case I, which represented the DRCOG "preferred" alternative, also assumed a net natural increase rate of 8.5/1000 persons, but a 1960's level migration (15,700 persons annually) through 1980 and a 1940-1970 thirty-year average level (15,100 persons annually) from 1980-2000. The resultant 1980-2000 populations were 1.6 and 2.2 million. The simplified method projected 1.5 and 2.1 million, values not quite the same. If 1975 is used as the base year, using the actual population in that year, the 1980 and 2000 forecasts become 1.6 and 2.2 million.

c. Population Sensitivities

Using the closed-form expression for total population growth derived in the previous section it is possible to determine analytically the sensitivity of forecast population to the two basic input assumptions, the net natural increase rate and the level of migration. This is done simply by taking the partial derivatives of Eq. (7) with respect to each of the two independent parameters.

The analytic sensitivities thus determined are expressed in the following form:

$$\frac{\partial P}{\partial m} = \frac{1}{r}\left[e^{r(t-t_0)} - 1\right] \tag{8}$$

$$\frac{\partial P}{\partial r} = \left(P_0 + \frac{m}{r}\right)(t-t_0)e^{r(t-t_0)} - \frac{m}{r^2}\left[e^{r(t-t_0)} - 1\right], \tag{9}$$

where these are the sensitivities of total population to migration level and net natural increase rate, respectively.

d. Review of DRCOG Forecast

The population growth alternative recommended by the DRCOG staff was Case I, with a Year 2000 population level of 2,175,000. This figure was subsequently modified by the Council of the DRCOG to add 175,000, principally in southeast Jefferson County. The final approved total was 2,350,000. The assumptions implicit in this figure differ from those in Case I. Although the net natural increase rate of 8.5/1000 persons remained the same, the migration level is higher in the approved forecast.

The migration level embedded in a population forecast may be determined approximately by inverting the simplified relation in Eq. (7). The migration level thus determined can be expressed as

$$m = r\left[\frac{P - P_0 e^{r(t-t_0)}}{e^{r(t-t_0)} - 1}\right] \qquad (10)$$

where P is the population in a future year t and P_0 is the population in the year t_0, with r being the net annual natural increase rate.

This relation can be used to determine the migration level necessary for the Denver regional population to reach 2,350,000 in the year 2000. Using the population in 1970 as a base and the net natural increase rate assumed in both Case I and the approved forecast, Eq. (10) predicts that a migration level of 22,328 persons annually would be required to reach the approved Year 2000 figure.

ANNEX C-2
NATIONAL AMBIENT AIR QUALITY STANDARDS

Pollutant	Type of Standard	Time Interval	Effective Year	Concentration ug/m^3	PPM
Carbon Monoxide	Federal	1 hour	1977	40,000	35
		8 hour	1977	10,000	9
Hydrocarbons (non-methane)	Federal	3 hour (6-9 a.m. only)	(see ozone)	160	0.24
Nitrogen Dioxide	Federal	1 year (arith.)	(undetermined)	100	0.05
Ozone (Oxidants)	Federal	1 hour	1977	160	0.08
Sulfur Dioxide*	Federal	24 hour	1975	365	0.14
	Primary	1 yr. (arith.)	1975	80	0.03
	Secondary	3 hour	1975	1,300	0.5
Particulates	Federal	24 hour	1975	260	--
	Primary	1 yr. (geo.)	1975	75	--
	Secondary	24 hour	1975	150	--
		1 yr. (geo.)	1975	60**	--
	State				
	Non-Designated Areas	24 hour	1970	150	--
		1 yr. (arith.)	1970	45	--
	Designated	24 hour	1973	200	--
			1976	180	--
			1980	150	--
		1 yr. (arith.)	1973	70	--
			1976	55	--
			1980	45	--

* Refer to table titled "Sulfur Dioxide Ambient Air Standards for the State of Colorado"

** Federal guideline only

Annex C-2 (Concluded)

SULFUR DIOXIDE (SO_2) AMBIENT AIR STANDARDS FOR THE STATE OF COLORADO

Micrograms Per Cubic Meter

	Maximum Allowable Increments Over Baseline ug/m^3		Maximum Allowable Concentrations ug/m^3
	Sulfur Dioxide Category I (formerly non-designated areas)	Sulfur Dioxide Category II	Sulfur Dioxide Category III (formerly designated areas)
Annual Mean	3 (.001)	15 (.005)	60 (.021)
24-hr. max.	15 (.005)	100 (.035)	260* (.091)
3-hr. max.	75 (.026)	700 (.245)	1300* (.455)

( ) = equivalent values in parts per million (1 ppm=2860 ug/m^3 at 0°C and 760 mm Hg (Torr)).

* Not to be exceeded more than once in a twelve-month period.

REFERENCES FOR APPENDIX C

1. "Continuing Air Quality Review Procedure," Joint Regional Planning Program, Technical Memorandum 8/03, March 1976 (Prepared by Colorado Division of Highways).

2. "Air Quality Guidelines," Federal Highway Administration, U. S. Department of Transportation, Federal-Aid Highway Program Manual, Vol. 7, Chap. 7, Sect. 9, Transmittal 105, 26 November 1974.

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